Advanced Design and Optimization of High Performance Combatant Craft:

Material Testing and Computational Tools

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Over the past several years, the use of advanced composites in high-speed boats for US Navy applications has been demonstrated in various platforms including the composite MAKO – delivered by Hodgdon Defense Composites in 2008. These applications show that advanced composite manufacturing, specifically closed mold infusion, have the potential to deliver boats that are stronger, lighter, inherently shock-absorbent, and more durable than conventional materials. Despite these initial demonstration successes, there are still barriers that need to be overcome before engineers can fully implement this new technology in the design, specification, and acquisition process for high-speed boats. The Project Team investigated three areas of research regarding the implementation of composite sandwich panels into naval hull designs. The three research areas investigated are:

- Evaluation of nondestructive testing techniques on foam cored sandwich panels
- Strain rate effects on polymeric foam cored laminates
- Impact resistance of foam cored sandwich panels with an interleaved layer.

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Preface

The technical report was developed by a University-Industry project team consisting of research engineers, faculty, graduate students and practicing engineers. The following individuals had primary responsibility for preparing the technical report.

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Executive Summary

Over the past several years, the use of advanced composites in high-speed boats for US Navy applications has been demonstrated in various platforms including the composite MAKO – launched by Hodgdon Defense Composites in 2008. These applications show that advanced composite manufacturing, specifically vacuum assisted resin transfer molding (VARTM), has the potential to deliver boats that are stronger, lighter, inherently shock-absorbent, and more durable than those manufactured with conventional materials. Despite these initial demonstration successes, there are still barriers that need to be overcome before engineers can fully implement this new technology in the design, specification, and acquisition process for high-speed boats. The Project Team investigated three areas of research regarding the implementation of composite sandwich panels into naval hull designs. The three research areas investigated are:

- Evaluation of nondestructive testing techniques on foam cored sandwich panels.
- Strain rate effects on polymeric foam cored laminates.
- Impact resistance of foam cored sandwich panels utilizing an interleaved fabric layer within the core.

The Project Team sought to develop a set of basic nondestructive testing (NDT) guidelines that can be used to efficiently identify and characterize defects in composite boats. Several methods were identified as possible techniques including shearography, thermography, and Structural Irregularity and Damage Inspection Routine (SIDER). Ultrasonic techniques (UT) were also employed as an additional technique. The techniques were evaluated to quantify the capabilities and limitations of each as a function of flaw size and type, laminate type, surface texture (e.g. mold side versus bag side), accessibility (one- or two-sided access), inspection speed, and sensitivity. Five unique sandwich laminate constructions intended to represent the typical range of laminations used in small to large sandwich hull construction, were fabricated for this study. This phase of the study also included the development of a numerical approach that could assess the effect of defects on residual strength and predict flaw propagation in foam cored sandwich panels. This tool has the potential to reduce the need for more extensive and expensive empirical evaluations. The tool was used in a trial study to assess fracture propagation of delaminations in sandwich panels undergoing flexural fatigue loading. The major findings of this study include:

- Shearography was successful at locating all of the delaminations in the panels and proved to be the fastest method to locate the defects. Shearography should be combined with a UT evaluation since this can provide the depth of the delamination within the laminate.
- The SIDER analysis was not able to identify delaminations in the foam cored sandwich panels, most likely due to boundary constraints. SIDER has had success in the past with fixed boundary conditions like those found in a subcomponent of a larger structure.
- Thermography was not able to identify the delaminations in the sandwich panels.
- The numerical delamination model developed using the macro programming language of a commercial FE code proved to be an efficient tool for generating fracture toughness predictions as a function of delamination size, position, and depth within the foam cored sandwich panels.
- The fatigue testing of the large sandwich panels was not successful at propagating the delaminations within the panel. The FE model confirmed that the strain energy release rate levels produced during the test were not sufficient to propagate the delaminations.

When used in the hull panels of high speed boats, structural foam cores are subject to slamming loads of high intensity, occurring at a rapid loading rate (five to 50 milliseconds). Traditional testing standards require that structural foams be tested at a much slower, quasi-static loading rate (two to three minutes to failure). Some studies have indicated that the shear strength of foam core is substantially higher when subjected to high strain rate loading; therefore, structural foam cores used in high-speed boat designs dominated by dynamic events, such as slamming loads, may be significantly overdesigned. The Project Team evaluated the effects of loading rate and temperature on two common foam core materials, polyvinyl chloride (PVC) and styrene acrylonitrile (SAN), at three foam core densities. A semi-empirical model was developed that describes the change in mechanical properties of the foam under these conditions, and it was correlated with the experimental flexural test results of sandwich constructions. The major results of this investigation include:

- When subjected to dynamic strain rates, shear modulus and strength increased by as much as 16% and 45%, respectively, over the same properties generated with quasi-static loading at standard temperature.
- The results of the subcomponent sandwich beam flexure tests, where the increase in properties was as much as 49% at standard temperature, were consistent with the dynamic response of the foam core material.
- The shear strength and stiffness properties of the foam core exhibited an inverse relationship with temperature.
- Shear material properties of the foam core laminates tested at temperatures above and below the standard environment resulted in increased properties when tested at higher strain rates.
- The properties generated during the sandwich beam flexure tests conducted at high and low temperatures exhibited an increase with increasing strain rate and an inverse relation with temperature. The relative increase in properties at a given strain rate increased with increasing temperature.
- A mechanics model based on a moment-curvature analysis was generated to model the foam cored sandwich panels. The model consistently under-predicted the results of the sandwich flexure tests and requires further development to overcome the current limitations to enable an analysis of plate structures.

Designers of high performance, high speed composite vessels are continuously implementing trade studies to derive the lightest weight structures while maintaining the best overall reliability and survivability. Naval design society rules do not specifically address impact damage to composite panels. Development of an approach to evaluate impact damage at the component (panel) scale would facilitate research in this area. Prior studies have shown that incorporating an interleaved skin within a lightweight sandwich panel has the potential to increase ultimate impact damage tolerance without significantly increasing the overall weight. In this case, the outer skin of a composite panel may be penetrated or damaged, but its watertight integrity is not violated and the vessel may continue with its mission.

In an effort to understand and quantify the low speed impact resistance of composite sandwich panels with an interleaved layer, the Project Team fabricated and tested 11 different laminate configurations under impact loading. The configurations were fabricated with an interleaved layer at various depths in the sandwich panel combined with different density foam core materials. The laminates were impacted with two different diameter impactors (tups), 15.9 mm (0.625 in.) and 51 mm (2.0 in.). The major findings of this study include:

- The laminate with the interleave layer on top of the foam core had the best performance when impacted with the 15.9mm (0.625 in.) tup.
- The laminate with the interleave layer 1/3 of the way into the foam core had the best performance when impacted with the 51 mm (2.0 in.) tup.
- Higher density foam cores generally showed improved performance over the lower density foam cores.
- Energies required to produce failure with the larger tup were approximately six times greater than those with the smaller tup.

This effort should lay the groundwork for sandwich laminate configurations with superior impact resistance, reliability, and with a better understanding of the inspection and design requirements for integration into naval hull designs.

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List of Symbols, Abbreviations, and Acronyms

ABS	American Bureau of Shipping
AEWC	AEWC Advanced Structures and Composites Center
APDL	ANSYS Parametric Design Language
ASTM	American Society of Testing and Materials
BGSM	Band Gapped Smoothing Method
C	Extent of the fine mesh region
C_c	Compression in the core.
C_f	Compression in the top skin
CFM	Continuous filament mat
COV	Coefficient of variation
D	Extent of the coarse mesh region; panel flexural stiffness; damage sum
DCB	Double cantilever beam
DNV	Det Norske Veritas
DOF	Degrees of freedom
E	Kinetic energy
E_1	Modulus of the top facesheet
E_2	Modulus of the bottom facesheet
E_b	Elastic modulus of the bottom facesheet
E_c	Elastic modulus of the core
E_t	Elastic modulus of the top facesheet
EI	Bending rigidity
ENF	End notched flexure
F_{off}	2% offset shear stress
F_{ult}	Ultimate shear strength
FE	Finite element
G	Core shear modulus; slope of the hyperbolic tangent function at the origin
G_c	Shear modulus of the core
G_I	Mode-I fracture toughness
G_{II}	Mode-II fracture toughness
G_{TOTAL}	Total fracture toughness or total strain energy release rate
G_{RATIO}	Fracture toughness ratio (G_{II} / G_{TOTAL})
GFRP	Glass fiber reinforced plastic
HDC	Hodgdon Defense Composites
HSB	Hodgdon Ship Building
HYI	Hodgdon Yachts Inc.
IR	Infrared
L	Length of the beam; length of support span
LVDT	Linear variable differential transformers
M(x)	Moment as a function of the x-coordinate

List of Symbols, Abbreviations, and Acronyms *(cont.)*

N	Quantity of specimens in the sample
N2C	Next Navy Composites
NDT	Nondestructive testing
NSWCCD	Naval Surface Warfare Center Carderock Division
OCS	Operating curvature shape
ODS	Operating deflection shape
ONR	Office of Naval Research
P	Load; ultimate load
POD	Probability of detection
PVC	Polyvinyl chloride
R	Stress ratio
SAN	Styrene acrylonitrile
SERR	Strain energy release rate
SF	Safety factor
SIDER	Structural Irregularity and Damage Inspection Routine
SLB	Single leg bending
S–N	Stress–number of cycles
T_1	Test statistic of the smallest value outlier
T_c	Tension in the core
T_f	Tension in the bottom skin
T_N	Test statistic of the largest value outlier
U	Panel shear rigidity
UT	Ultrasonic testing
V	Shear force
V(x)	Shear force as a function of the x-coordinate
VCCT	Virtual crack closure technique
X	Longitudinal direction coordinate
X_{Li}	Nodal force in the x-direction
Y	Transverse direction coordinate
Y_{Li}	Nodal force in the y-direction
Z	Vertical direction coordinate
b	Specimen width; section width; width of the crack front
c	Distance from the extreme top fiber to the neutral axis; core thickness
d	Sandwich thickness
del_C	Coarse mesh element size
del_F	Fine mesh element size
del_S	Shell element mesh size
del_Z	3D element size in the thickness direction
h	Total height of the sandwich laminate

List of Symbols, Abbreviations, and Acronyms *(cont.)*

h_b	Thickness of the bottom facesheet
h_c	Thickness of the core
h_t	Thickness of the top facesheet
kAG	Shear rigidity
m	Mass
s	Sample standard deviation
t	Facesheet thickness
t_1	Thickness of the top facesheet
t_2	Thickness of the bottom facesheet
u-P	Displacement-pressure
$\boldsymbol{u}_{L\ell}$	x-coordinate of the upper node
$\boldsymbol{u}_{L\ell^*}$	x-coordinate of the lower node
v	Velocity
$\boldsymbol{w}_{L\ell}$	z-coordinate of the upper node
$\boldsymbol{w}_{L\ell^*}$	z-coordinate of the lower node
w_{max}	Mid-span deflection
$\bar{x}$	Sample mean (average)
x_i	Measured property in the data set
x_1	Smallest result in a data set
x_N	Largest result in a data set
z	Distance from the bottom of the sandwich laminate
ΔA	Area virtually closed
ΔP	Change in load
Δa	Length of the element in the x-direction
$\Delta\delta$	Total beam deflection
$\Delta\delta_B$	Beam deflection due to bending
$\Delta\delta_S$	Beam deflection due to shear
ΔQS	Percent change in the results relative to the quasi-static speed test results
Δ21°C	Percent change in the results relative to the standard temperature test results
$\Delta\gamma$	Small offset on each side of the point of interest
γ	Shear strain; shear strain in the core
ε_x	Selected normal strain at the extreme top fiber
σ	Stress on face due to bending
σ_{face}	Normal stress in the facesheet at failure
τ	Shear stress; core shear stress
τ_c	Shear stress in the core
τ_{fail}	Shear stress at failure
τ_{max}	Asymptote of the hyperbolic tangent function

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1 Introduction

This is the final report for ONR project titled ADVANCED DESIGN AND OPTIMIZATION OF HIGH PERFORMANCE COMBATANT CRAFT: MATERIAL TESTING AND COMPUTATIONAL TOOLS, under contract N00014-10-C-0037. Fabrication work was performed by Hodgdon Defense Composites, LLC (HDC) and Hodgdon Yachts, Inc. (HYI). Laboratory testing and data analysis were conducted by HDC and the AEWC Advanced Structures and Composites Center at the University of Maine (AEWC). Analytical tool development was performed by AEWC. The project work was conducted from May 2010 to November 2011.

1.1 Problem Statement

Over the past several years, the use of advanced composites in high-speed boats for US Navy applications has been demonstrated in various platforms including the composite MAKO – launched by Hodgdon Defense Composites in 2008. These applications show that advanced composite manufacturing, specifically VARTM, have the potential to deliver boats that are stronger, lighter, inherently shock-absorbent, and more durable than conventional materials (e.g. aluminum). Further, prior research by the University of Maine, Virginia Tech, and others has developed a better understanding of variability in naval composites[1-9], which will eventually lead to more efficient and reliable uses of advanced materials in naval applications.

Despite these initial demonstration successes, there are still barriers that need to be overcome before engineers can fully implement this new technology in the design, specification, and acquisition process for high-speed boats.

Defects (e.g. delaminations, disbonds, and voids) will occur even in advanced composite manufacturing processes, but as yet there is no method for establishing defect tolerance or efficiently identifying defects through nondestructive techniques. A numerical approach that could assess a defect's impact on residual strength and predict flaw propagation would help define defect tolerance and establish nondestructive inspection methods and frequency. This tool would also reduce the need for more extensive and expensive empirical evaluations.

When used in the hull panels of high speed boats, structural foam cores are subject to slamming loads of high intensity, occurring at a rapid loading rate (five to 50 milliseconds). Traditional testing standards require that structural foams be tested at a much slower, quasi-static loading rate (two to three minutes to failure). Initial studies indicate that the shear strength of foam core is substantially higher when subjected to high strain rate loading[10-13]. Therefore, structural foam cores used in high-speed boat designs dominated by slamming loads may be significantly overdesigned.

Designers of high performance, high speed composite vessels are continuously implementing trade studies to derive the lightest weight structures while maintaining the best overall reliability and survivability. Naval design society rules do not specifically address impact damage to composite panels. The level of tolerance to impact is generally left to owner preferences. Development of an approach to evaluate impact damage at the component (panel) scale would facilitate research in this area. Specifically, incorporating an interleaved skin within a lightweight sandwich panel has the potential to increase ultimate impact damage tolerance without significantly increasing the overall weight[14, 15]. In this case, the outer skin of a composite panel may be penetrated or damaged, but its watertight integrity is not violated and the vessel may continue with its mission.

1.2 Project Objectives

The project team sought to develop a set of basic nondestructive testing (NDT) guidelines that can be used to efficiently identify and characterize defects in composite boats. Several methods were

evaluated to quantify the capabilities and limitations of each as a function of flaw size and type, laminate type, surface texture (e.g. mold side versus bag side), accessibility (one- or two-sided access), inspection speed, and sensitivity. The proposed guidelines employed multiple levels of NDT. The project team determined which types of NDT methods can detect the flaws, and also determined the change in material properties resulting from the flaws via calculation and testing. With these results, the project team developed guidelines and methodologies for nondestructive testing and flaw rejection that incorporate prior research by ONR, which were combined to improve manufacturing quality and potentially allow the use of quality-based partial safety factors.

The project team also evaluated the effects of loading rate and temperature on two foam core materials and three foam core densities and from this test data developed semi-empirical models that describe the change in foam mechanical properties under these conditions. These models can be applied to a variety of future research and design programs. Prior studies indicate that the shear strength and stiffness of foam core is substantially (up to 60%) higher when subject to high strain rate loading [10]. This effort sought to quantify the increase in strength and stiffness for the selected foam core materials and identify the resulting increase in design margin for various sandwich laminates in an effort to reduce conservatism for designs dominated by slamming loads.

In an effort to understand and quantify the low speed impact resistance of composite sandwich panels with an interleaved layer, the project team fabricated and evaluated a number of laminate configurations under impact loading. A variety of laminate configurations fabricated with an interleaved layer at various depths in the sandwich panel combined with different density foam core materials were evaluated. This effort lays the groundwork for implementing sandwich laminate configurations with superior impact resistance in future studies and eventual integration into improved hull designs.

2 Methodology

The following methodology outlines the approach that was used during the project to achieve the objectives. Investigations were conducted in three focus areas: 1) Evaluation of nondestructive testing techniques on foam cored sandwich panels; 2) Strain rate effects on foam cored laminates; and 3) Impact resistance of foam cored sandwich panels with an interleaved layer. Details of the three focus areas are described in the remainder of this section.

2.1 Research Activities

2.1.1 Nondestructive Testing Evaluation

The project team identified NDT technologies that can be used to test large areas (e.g. composite decks and hulls). The candidate NDT methods are thermography, shearography, and Structural Irregularity and Damage Inspection Routine (SIDER). Thermal imaging has been used to identify damage in single skin composite vessels, although the insulating properties of foam and balsa may limit its use with cored structures. SIDER, a technique whereby the structure is vibrated with an instrumented impact hammer and acceleration data is used to identify damaged regions, has been used to identify defects on GFRP sandwich structures[16]. Shearography uses laser interferometry to detect very subtle surface deformations when the structure is subjected to a load. For more precise measurement and characterization of defects, ultrasonic testing (UT) can be used. UT has been successfully employed to identify defects in both cored and single-skin structures. One of the methods listed above may be considered as a complement to UT for local characterization of defects.

The defect tolerance of a rectangular, simply supported composite sandwich panel was modeled with finite elements (FE) using the ANSYS Parametric Design Language (APDL). A combined shell/3D model was used to predict behavior at the delamination front while reducing computational requirements. This model is capable of predicting the residual strength versus flaw-size for a panel with various defect sizes, shapes, and locations. Failure criteria considered were structural (stress and strain) and fracture mechanics (crack growth). Material failure can be evaluated against composite failure theories such as maximum stress or strain. The virtual crack closure technique (VCCT) was used to calculate strain energy release rate (SERR) and mode mixity to compare with fracture failure criteria. Results can be used to define maximum permissible flaw size depending on defect location and applied loads and estimate required inspection frequency. This FE delamination model approach can be modified to predict the damage behavior of a hull panel by applying appropriate boundary conditions and applying loads (or displacements) extracted from a full structural model.

A group of 432 mm × 1816 mm (17 in. × 71.5 in.) sandwich panels were fabricated with and without engineered defects. These panels provide a platform for evaluating the performance of each NDT method and are also used in structural static and fatigue testing to measure flaw growth with fatigue cycles and ultimate/residual strength. Empirical results were compared to numerical models.

A comprehensive set of foam core and skin material combinations was selected. Skin laminates included a range of E-glass/vinyl ester layups indicative of larger composite vessels and carbon and carbon-hybrid/epoxy layups characteristic of lighter, high performance, high speed vessels. Foam core materials include polyvinyl chloride (PVC) plastic foam and styrene acrylonitrile (SAN) plastic foam, each with a selection of three densities. Both the PVC and SAN foams are typically used for boat hull construction, with the SAN foam providing a higher elongation at failure.

NDT guidelines for inspecting various sandwich laminates are provided. Considerations include: constituent materials, relative size of area to be inspected, accessibility, surface finish, nature of defects, etc. The recommendations consider the capabilities and limitations of each method and the sensitivity to defect size and location.

2.1.2 Strain Rate Effects on Foam Core

In order to investigate the effects of strain rate and temperature on sandwich panels, the project team selected some standard foam core materials to test at various strain rates and temperatures. The foam core was tested in direct shear to quantify its properties under different loading rates and temperatures. A mechanics model was created to measure the change in foam core properties under different loading speeds and temperatures. The selected foam cores were fabricated into sandwich panels that matched those used in the NDT described above. These panels were tested to measure the relative effect of changing foam core properties on sandwich structural performance and to validate the mechanics model.

Foam core shear properties are determined using ASTM C273 *Shear Properties of Sandwich Core Materials*[17] (C273) at three strain rates (quasi-static, intermediate, and slamming) and at three temperatures (low, standard, and high). Tension and compression tests are performed on the laminate facings to obtain the remaining properties needed to describe the response of the sandwich laminates during validation tests. ASTM D3039 *Tensile Properties of Polymer Matrix Composite Materials* [18] (D3039) is used to obtain the tensile properties for the mold side (tension) facing, while ASTM D6641 *Determining the Compressive Properties of Polymer Matrix Composite Laminates Using a Combined Loading Compression (CLC) Test Fixture*[19] (D6641) is used to obtain compression properties for the bag side (compression) facing, These laminate tests are performed at quasi-static speed only.

A model is proposed that relates the specified strain rate to the foam core shear properties. This model uses classical cored-laminate theory to predict the response of the sandwich laminates during flexural testing. ASTM C393 *Core Shear Properties of Sandwich Constructions by Beam Flexure* [20] (C393) is used for this testing. The mechanics model is validated with the C393 test results.

2.1.3 Impact Resistant Laminates

The project team has selected some core materials typically used in small craft construction with carbon facesheets to test the effects of interleaving on impact resistance of cored laminations suitable for naval small craft hull construction. An E-glass interleave layer will be placed at different depths within the foam core to determine if its addition and positioning within the foam core can improve the impact resistance of cored constructions. Hodgdon Defense Composites has designed and constructed a drop weight test frame to perform the impact testing. These tests are conducted utilizing guidance from ASTM D7136/D7136M *Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop Weight Impact Event*[21](D7136). Complete details are available in Appendix A of this report.

2.2 Population and Sampling

2.2.1 Large Test Panels

Five unique sandwich construction types were selected for NDT, fatigue, and static testing as presented in Table 1. The first group, Types 1 and 2, consist of PVC foam cores with E-glass/vinyl ester skins. These panels represented hull and deck laminates in a large (e.g. 43 m [140 ft]) vessel. Types 3 through 5 are constructed of SAN foam cores with carbon, carbon-aramid, or aramid skins with epoxy resin. This group represented small to medium craft (9–27 m [30–90 ft]). These

materials and arrangements cover a wide range of options that could be seen in composite vessels. As a result, the inspection method and flaw growth assessments provide a comprehensive examination of performance versus skin type. However, such a group limits the number of specimens for each material type due to budget and schedule constraints.

As shown in Table 1, each of the five sandwich construction types included six panels:

- Two control panels with no engineered defects.
- One with a defect on the mold side of the panel within the skin.
- One with a defect on the mold side of the panel at the skin-core interface.
- One with a defect on the bag side of the panel within the skin.
- One with a defect on the bag side of the panel at the skin-core interface.

The control panels provide baseline strength and stiffness values of undamaged panels. The combinations of defect placement (mold versus bag side) and location (skin or skin-core) satisfy multiple purposes. The smooth mold side and rougher bag side are expected to cause differences in performance for some inspection methods (e.g. a large portion of the UT signal scatters at a rough surface preventing sound penetration and prohibiting inspection). Some inspection methods are

Table 1: Large sandwich panels for NDT and fatigue testing.

Sandwich Type	Face-Sheet Materials	Foam Core Type & Nominal Thickness	Sandwich Construction[a, b]	Defect Placement	Defect Location	# of Panels
1	E-Glass/ Vinyl-ester *(heavy)*	Divinycell H130 *76.2 mm (3.0 in.)*	E-CFM/E-LTM 1603/ E-LTCFM 2415/E-LTCFM 3610_2 **Core/**E-CFM/**Core** E-LTCFM 3610_2/E-LTCFM 2415/ E-LTM 1603	control	n/a	2
				mold	within skin	1
					skin-core	1
				bag	within skin	1
					skin-core	1
2	E-Glass/ Vinyl-ester *(heavy)*	Divinycell H100 *38.1 mm (1.5 in.)*	E-CFM/E-LTM 1603/ E-LTCFM 3610_2 **Core** E-LTCFM 3610_2/E-LTM 1603	control	n/a	2
				mold	within skin	1
					skin-core	1
				bag	within skin	1
					skin-core	1
3	Carbon/Epoxy *(medium)*	Corecell M100 *50.8 mm (2.0 in.)*	E-veil/K-BXM 1308/C-BX 1800/ C-LA 1812/C-BX 1800 **Core/**E-CFM/**Core** C-BX 1200/C-LA 1812/C-BX 1200	control	n/a	2
				mold	within skin	1
					skin-core	1
				bag	within skin	1
					skin-core	1
4	Carbon/Epoxy *(medium)*	Corecell M80 *25.4 mm (1.0 in.)*	E-veil/C-BX 1800/C-LA 1812/ C-BX 1200 **Core** C-BX 1200/C-LA 1812/C-BX 1200	control	n/a	2
				mold	within skin	1
					skin-core	1
				bag	within skin	1
					skin-core	1
5	Carbon-Aramid/ Epoxy *(light)*	Corecell M80 *38.1 mm (1.5 in.)*	E-Veil/K-BXM 1308_3/E-CFM **Core** C-LT 1800/C-BX 1200	control	n/a	2
				mold	within skin	1
					skin-core	1
				bag	within skin	1
					skin-core	1
[a] "E-" denotes E-glass reinforcement, "C-" denotes carbon reinforcement, and "K-" denotes aramid reinforcement. [b] Data sheets for all of the fabric and core materials is provided in Appendix B.				**Total Specimens**		**30**
				Nominal Size	0.43 m x 1.82m (1.4 ft × 6.0 ft)	

expected to identify skin-core delaminations better than others. The difference in SERR and fracture toughness for cracks in the skin versus cracks at the skin-core interface can be compared.

Table 2 lists the resins and hardeners that were used to infuse the test panels. The panels constructed with E-glass fabric facings used vinyl ester resin, while the carbon and carbon/aramid hybrid facings used epoxy resin.

Table 2: Infusion resins for sandwich panel fabrication.

Resin Type	Manufacturer	Resin	Hardener	Ratio by Wt.
Vinyl Ester	CCP	Epovia RF1001L-00	ARA Luperox DDM-9	100:1.5
Epoxy	Pro-Set	LV117-1	237-1	100:30

Table 3 lists the fabrics that were used to form the skins of the sandwich panels. Table 4 lists the foam core materials that were used in the sandwich panels. For infusion purposes, the foam core material included 1.59 mm (0.0625 in.) diameter perforations (through the thickness) spaced 25.4 mm (1.0 in.) apart in the Corecell foam and 19.1 mm (0.75 in.) apart in the Divinycell foam.

Table 3: Reinforcement fabrics for sandwich panel construction.

Material ID	Fabric Type	Manufacturer	Architecture	Areal Wt. *gm/m^2 (oz/yd^2)*	Dry Thick *mm (in.)*
E-LTM 1603	E-glass	Vector Ply	0/90°	643 (18.96)	0.69 (0.027)
E-LTCFM 2415	E-glass	Vector Ply	0/90°	1263 (37.24)	1.68 (0.066)
E-LTCFM 3610	E-glass	Vector Ply	0/90°	1540 (45.42)	1.42 (0.056)
M8635 CFM *(E-CFM)*	E-glass	Owens Corning	random	450 (13.5)	-
Finishmat D7760 *(E-veil)*	E-glass	Lantor	random	60.0 (1.77)	0.30
C-LA 1812	Carbon	Vector Ply	0°	637 (18.8)	0.99 (0.039)
C-BX 1800	Carbon	Vector Ply	± 45°	580 (17.11)	0.89 (0.035)
C-BX 1200	Carbon	Vector Ply	± 45°	400 (11.80)	0.61 (0.024)
C-LT 1800	Carbon	Vector Ply	0/90°	630 (18.58)	0.89 (0.035)
K-BXM 1308	Aramid	Vector Ply	± 45°	747 (22.02)	-
Material specifications are available in the data sheets found in Appendix B					

Table 4: Foam core materials for sandwich panel construction.

Material	Manufacturer	Nomenclature	Nominal Density *kg/m^3 (lb/ft^3)*
PVC	Diab (Divinycell)	H130	130 (8.1)
PVC	Diab (Divinycell)	H100	100 (6.3)
SAN	Gurit (Corecell)	M100	107.5 (6.7)
SAN	Gurit (Corecell)	M80	85 (5.3)

The Divinycell H Grade Core lists a typical density variation of ±10%. This means that H130 foam core material has a density between 117 and 143 kg/m^3 (7.29 and 8.91 pcf) and the H100 foam core material has a density between 90 and 110 kg/m^3 (5.67 and 6.93 pcf). The Corecell M-foam

density variation for the M80 foam core is ±4.7% (81-89 kg/m^3) and for the M100 foam core is ±7.0% (100-115 kg/m^3). The variation in density within a provided foam core material could affect the testing through increased variability in the results.

2.2.2 ASTM C273 Specimens

The project team selected two common foam core materials, PVC and SAN, for the strain rate testing. Three densities of each foam core material were selected to quantify the standard range of densities. The foam core sheet material details are presented in Table 5. The specimen size was 50.8 mm x 457 mm (2 in. × 18 in.) for the PVC foam core and 50.8 mm x 432 mm (2 in. x 17 in.) for the SAN foam core. The difference in specimen length for the different foam cores was because the PVC sheets were 38.1 mm (1.5 in) thick, while the SAN sheets were 31.8 mm (1.25 in.) thick. The C273 test standard specifies that the load line must pass through the specimen diagonally; to satisfy this requirement for the thinner SAN foam core, the length must be shortened. Six specimens were tested for each of the three load rates and three test temperatures, for a total of 324 specimens for the C273 test. The parameter matrix for the C273 tests is shown in Table 6.

Table 5: Foam core sheet specifications used for C273 testing.

Foam Core			Length	Width	Thickness	Nominal Density
Material	*Manufacturer*	*ID*	*mm (in.)*	*mm (in.)*	*mm (in.)*	*kg/m^3 (lb/ft^3)*
PVC	Diab (Divinycell)	H80	2175 (85.6)	1220 (48.0)	38.1 (1.5)	80 (5.0)[a]
PVC	Diab (Divinycell)	H100	2000 (78.7)	1000 (39.4)	38.1 (1.5)	100 (6.3)[a]
PVC	Diab (Divinycell)	H130	1830 (72.0)	900 (35.4)	38.1 (1.5)	130 (8.1)[a]
SAN	Gurit (Corecell)	M80	2275 (89.6)	1130 (44.5)	31.8 (1.25)	85 (5.3)[b]
SAN	Gurit (Corecell)	M100	2275 (89.6)	1130 (44.5)	31.8 (1.25)	107.5 (6.7)[c]
SAN	Gurit (Corecell)	M130	2045 (80.5)	1015 (40.0)	31.8 (1.25)	140 (8.7)[d]

[a] Typical density variation is ±10% for Divinycell H grade foams.
[b] Typical density variation is ±4.7%.
[c] Typical density variation is ±7.0%.
[d] Typical density variation is ±7.1%.

2.2.3 ASTM C393 Specimens

The same sandwich construction types that were created for the large panel testing, as presented in Table 1, were used for the C393 specimens. The panels were fabricated in a size that corresponds to the maximum available size of the foam core material. Specimens were cut from these panels at a width-to-thickness ratio of 2:1 and length-to-thickness ratio of 10:1, except for panel type 1 which has a length-to-thickness ratio of 8:1. The 8:1 ratio was used for panel type 1 to avoid longer specimens that would require very high load rates. The combination of the three load rates and three temperatures results in nine test conditions. Six specimens were tested at each test condition for each of the five panel types, resulting in a total of 270 specimens for the C393 tests. The parameter matrix for the C393 tests is shown in Table 6

Table 6: Parameter matrix for the C273 and C393 tests.

Strain Rate	Temperature					
	Low		***Standard***		***High***	
	C273 Foam Cores	*C393 Foam Cores*	*C273 Foam Cores*	*C393 Foam Cores*	*C273 Foam Cores*	*C393 Foam Cores*
Quasi-Static	H80 H100 H130	H100 H130	H80 H100 H130	H100 H130	H80 H100 H130	H100 H130
Intermediate	M80 M100	M80 M100	M80 M100	M80 M100	M80 M100	M80 M100
Slamming	M130		M130		M130	

2.2.4 Sandwich Facesheet Specimens

Material properties of the facings of the sandwich panels were required to use as input for the C393 predictive model. Facing material property tests were conducted at the standard temperature only. The D3039 standard was used to determine the tensile strength and stiffness of the mold side (tension) facing, and the D6641 standard was used to determine the compression strength and stiffness of the bag side (compression) facing. The facing material test specimens were obtained from the same sandwich panels that were used to obtain the C393 test specimens. The facings were removed from the foam core using a band saw, and the test specimens were cut using a wet saw with diamond coated tooling. The D3039 specimens were 25.4 mm x 254 mm (1 in. x 10 in.), while the D6641 specimens are 12.7 mm x 140 mm (0.5 in x 5.5 in.). Six specimens were prepared from each of the five sandwich panel types, for each facing, for a total of 30 tension specimens and 30 compression specimens.

2.2.5 Impact Test Panels

Four different interleaving variations (designated A-D) were constructed with an E-Glass interleaving layer and carbon facesheets. The interleaving variations, relative to the impact surface of the panels, were as follows:

- Group A has the E-glass layer at the skin/core interface. (no interleaving).
- Group B has the E-glass layer located 1/3 of the way into the core material.
- Group C has the E-glass layer located 1/2 of the way into the core material.
- Group D has the E-glass layer located 2/3 of the way into the core material.

In addition to the baseline groups fabricated with H100 foam core; subgroups were fabricated that contain the H100 core combined with higher density core materials to determine core density effects on impact resistance. A total of 11 different laminates were fabricated for the impact testing and are presented in Figure 1. Regardless of the interleave location, or core density, each configuration contained a total nominal core thickness of 38 mm (1.5 in.)

Specimen size was 254mm x 254mm (10 in. x 10 in.) with a nominal thickness of 43 mm (1.7 in.). Specimens were visually inspected for defects and were stored in the test environment a minimum of 24 hours prior to testing. Complete details on specimen fabrication and specimen preparation are available in the Impact Report in Appendix A.

Two different hemispherical tipped impactor heads (tups) were used for the impact testing: a 15.9 mm (0.625 inch) diameter tup and a 51 mm (2.0 in.) diameter tup. The panels were impacted with different energy levels by adjusting the weight and/or drop height of the apparatus. Five replicates were tested for a given laminate at a given energy level.

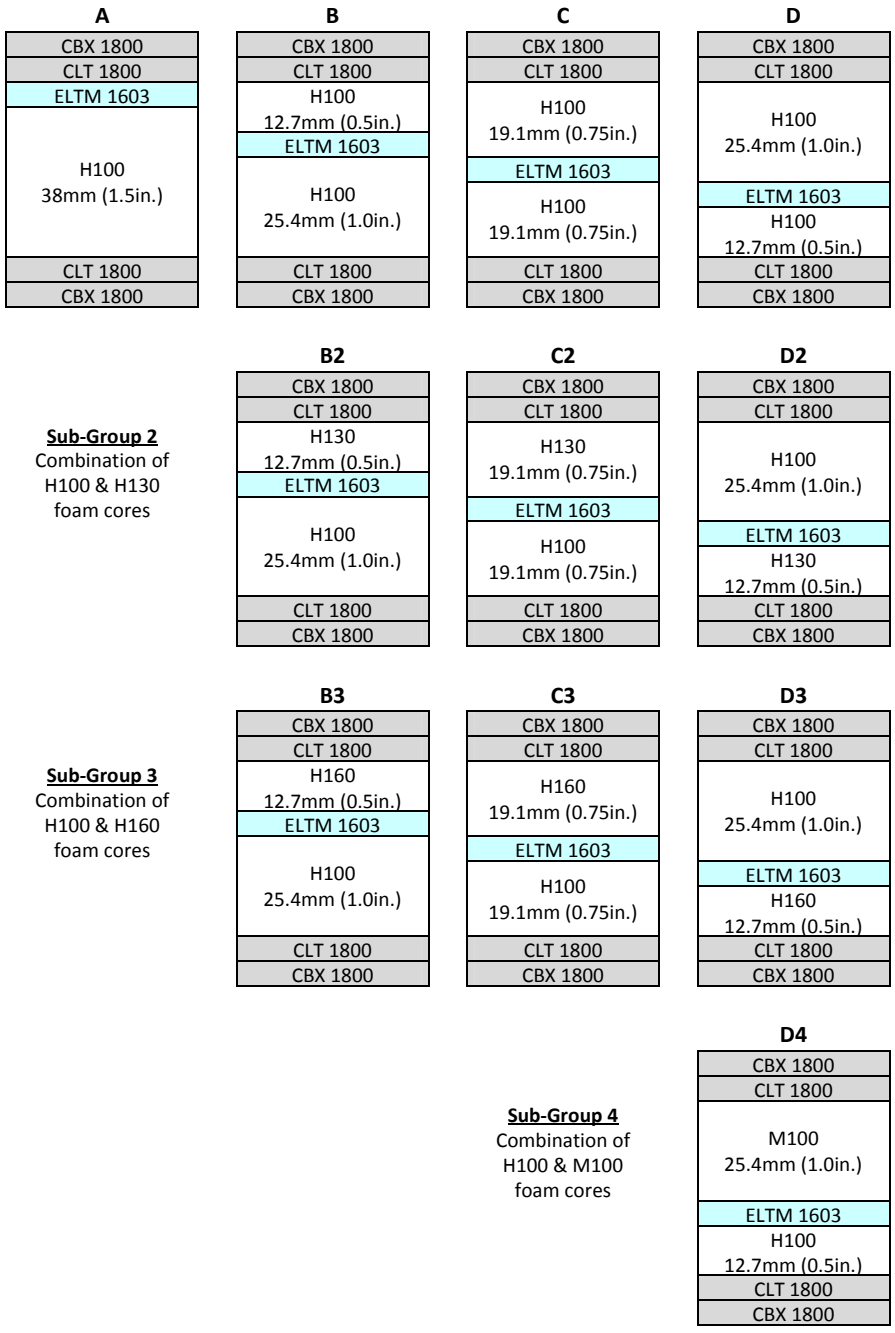


Figure 1. Sandwich panel laminate constructions for impact testing.

2.3 Equipment and Instrumentation

2.3.1 Nondestructive Testing

An FLIR SC620 infrared (IR) camera for conducing thermography inspections was purchased by AEWC. This portable camera along with the accompanying ExaminIR analysis software is a high performance IR system used for science and research applications. It has 640×480 resolution, a temperature range of -40°C to 500°C (-40°F to 932°F), accuracy of ±2°C (±3.6°F), 0.65 mrad spatial resolution, and a thermal sensitivity of ≤55 mK. Data (including full field radiometric temperature measurements) are captured either as still images or streaming video. Changes in heat transfer rate (and therefore surface temperature) due to internal flaws create an image that highlights various defects. A photograph of the SC620 is provided in Figure 2. A data sheet with complete specifications for the FLIR SC620 is included in Appendix C.



Figure 2: FLIR SC620 high performance infrared inspection system.
(source: Manufacturer's data sheets)

A laser interferometry system was rented from Dantec Dynamics for performing shearography inspections. Shearography is a non-contact, full field measurement system requiring no surface preperation. The system consists of a miniaturized shearography sensor with integrated high resolution CCD and variable computer controlled shear optics. The integrated laser diode array provides illumination and projects a speckle pattern on the surface of the part. Microscopic surface deformations caused by internal flaws are measured when thermal, mechanical, or vacuum pressure loading is applied. The Q-800 system is a tripod mounted camera that uses heat loading to inspect the part (Figure 3). The Q-810 is a surface mount system that produces a vacuum pressure loading. Data sheets with complete specifications for the Dantec shearography equipment are included in Appendix C.

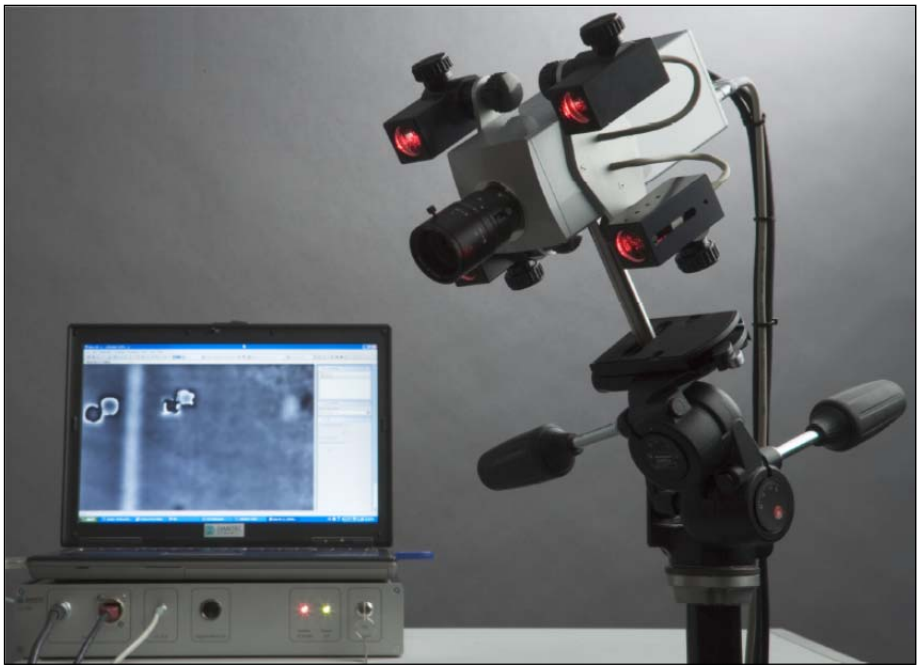


Figure 3: Dantec dynamics Q-800 laser shearography system.
(source: Manufacturer's data sheets)

A modal impact test system for measuring vibration data to support the SIDER analysis was purchased by AEWC. The system consists of an instrumented hammer (PCB 086D05; ±22.24 kN [±5000 lbf] peak measurement range, and 0.23 mV/N [1.0 mV/lbf] sensitivity), Integrated Circuit Piezoelectric accelerometers (PCB 333B32; ±490 m/s^2 [±50 g] peak measurement range, 0.5 to 3000 Hz frequency range, and 10.2 $mV/(m/s^2)$ [100 mV/g] sensitivity), and a digital signal analyzer (Data Physics SignalCalc ACE/Quattro; 120 dB dynamic range, 40 kHz analysis bandwidth). The modal system components are presented in Figure 4. The modal equipment is used to acquire the 2D mode shapes, which are then converted to curvature. Local curvature deviations from a smooth curve fit indicate the potential for a defect. Data sheets with complete specifications for the modal impact test system are included in Appendix C.



Figure 4: Modal testing components
(source: Manufacturer's data sheets)

A GE Phasor XS ultrasonic flaw detector (Figure 5) was used to perform UT of the defects identified in the large panels and to perform Probability of Detection (POD) studies of smaller defect panels. Based on the initial trials to determine depth of penetration and resolution performance two different probes were used for inspection. A 12.7 mm (0.5 in.) 2 MHz probe was used for the carbon panels, and a 25.4 mm (1 in.) 0.5 MHz probe was used for the other sandwich laminates. An Exosen general purpose couplant was used during inspection to couple the probe to the inspected surface. A data sheet with complete specifications for the GE Phasor XS ultrasonic flaw detector is included in Appendix C.



Figure 5: GE Phasor XS ultrasonic flaw detector.
(source: Manufacturer's data sheet)

2.3.2 Servo-hydraulic Testing

All tests involving the mechanical loading of specimens were performed on servo-hydraulic actuated test machines in the AEWC structural and mechanical testing laboratories. In each case, the actuators were operated under computer control with either load or position as the primary feedback. Instron Fast Track and Wave Matrix software programs were used to conduct the static and fatigue testing, respectively.

The large panel flexural tests were performed using an Instron servo-hydraulic actuator with a 1500 kN (337 kip) load capacity for the static tests, and with a 250 kN (56.2 kip) load capacity for the fatigue tests. Static testing to failure was performed to characterize the average load capacity of two samples for each panel type. The average static load capacity was used to define the fatigue test loading spectrum. Fatigue testing was run in tri-modal control within the Instron Wave Matrix software. Each fatigue sequence was set to run in position control with load targets to achieve accurate and precise load control. Peak and trough data was collected periodically throughout the duration of the test.

The foam core shear testing, following ASTM C273-07, was performed on an Instron 8801 servo-hydraulic testing machine with a 100 kN (22.5 kip) load capacity as shown in Figure 6. The foam core specimen for each test was bonded with a urethane adhesive to rigid steel load plates, which were mounted to the test machine through self-aligning couplings. The test fixture is designed to provide a load-path that passes through diagonally opposite corners of the foam core specimen. The tests were performed using a constant speed displacement control. A 100 kN (22.5 kip) capacity load cell was used for load measurement. Relative displacement of the load plates was measured using two linear variable differential transformers (LVDT), one on each side of the specimen.

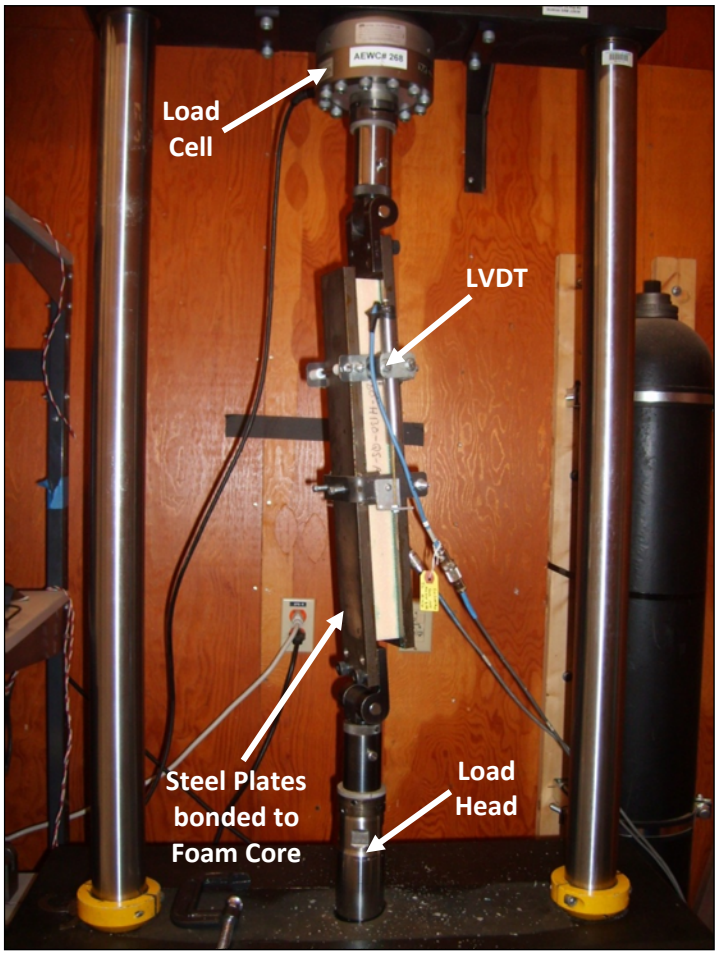


Figure 6: ASTM C273 test setup.

Sandwich beam flexure tests following ASTM C393-06 were performed using a high-speed 100 kN (22.5 kip) capacity actuator manufactured by Parker. The three-point loading test was arranged so that the beam carrying the end supports was mounted to the actuator. The load head was mounted directly to the 100 kN (22.5 kip) load cell, which in turn was mounted directly to a plate fastened to the laboratory floor (Figure 7). The support span was different for each sandwich panel type, and was at least eight times the total panel thickness. The applied loads were distributed over the panel surface at the two end supports by 38 mm (1.5 in.) wide (in the specimen longitudinal direction) flat steel plates, with 3.2 mm (0.125 in.) thick rubber (60 Shore-A durometer) pads between the plates and panel surface. The center load head for panel types 1, 2, 3 and 5 was 133 mm (5.25 in)

wide with a 508 mm (20.0 in) radius on the surface contacting the specimen. This surface was covered with the same rubber material as the support pads. Figure 8 shows the section shape of the load head. This contoured load head was designed to reduce the effects of foam core compression and bending stresses in the lower facing at the load head edges. The load head for panel type 4 was the same as the end support pads. The wider contoured load head was not appropriate for panel type 4 due to the short support span and predicted low ultimate loads. The tests were performed in position control with monotonic loading. The centerline deflection of the specimens was measured using a string potentiometer during the tests.

A complete listing of test equipment and instrumentation used for the tests performed at the AEWC laboratories is presented in Appendix C.

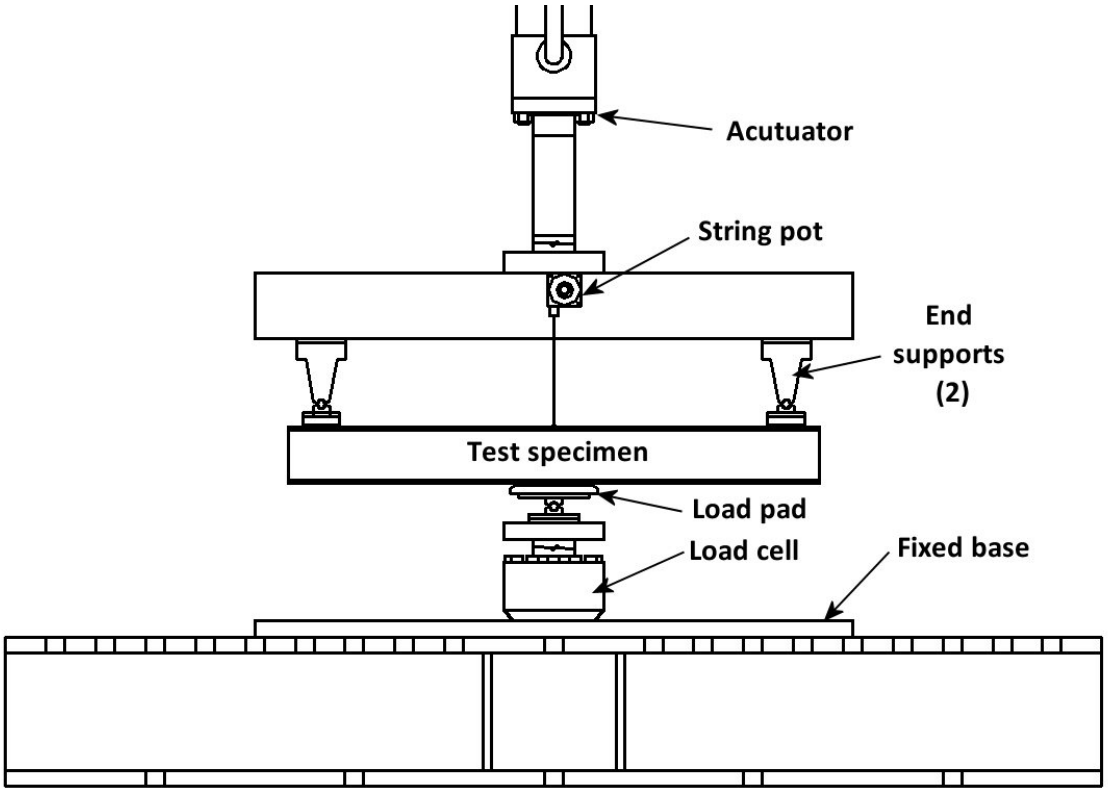


Figure 7: ASTM C393 setup.

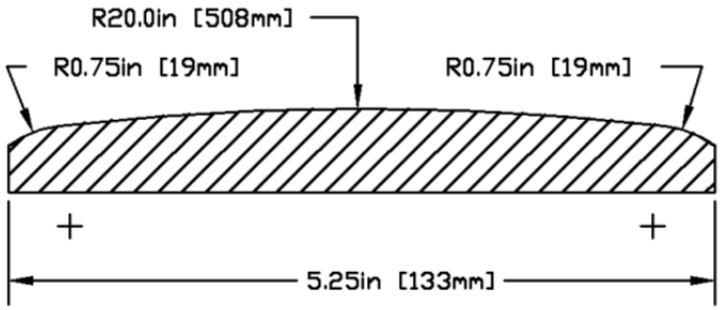


Figure 8: Load head (load pad) section shape used for panel types 1, 2, 3 and 5.

2.3.3 Impact Testing

An impact testing machine was designed and built by HDC utilizing guidance from ASTM Standard D7136/D7136M. A general description of the apparatus is presented below, with the complete details available in Appendix A. An overall view of the apparatus is presented in Figure 9a.

The apparatus is constructed of pultruded composite angles and channels. Two T guide rails are installed on the inside surfaces of the vertical C channels. A carriage is attached to the T rails via four sliding bearings. The carriage is constructed of aluminum sheet with a steel reinforcing plate installed at the bottom inside surface as shown in Figure 9b. Accommodations were made for the addition of steel weights in order to increase the energy delivered through the stainless steel hemispherical impactor spike (tup). The tup is attached to the carriage with a tup adapter. The adapter allows for the interchanging of various sized tups without recalibration of the optical gate.

The tups are made of stainless steel (hardness rating 60). A range of tup sizes were fabricated for use with the test frame, but only the 15.9 and 51 mm (0.625 and 2.0 in.) diameter tups were used in this study. The tups were highly polished to minimize friction when the test specimen is penetrated. The hemispherical shape of each tup tip was produced as specified in the ASTM Standard D7136/D7136M.

The base of the testing apparatus is comprised of a concrete pad with a stainless steel plate designed to support a 254 x 254 mm (10 x 10 in.) specimen. The front side of the support pad has two guide pins installed to provide for consistent placement of the test specimen. Specimen clamping is provided via four table clamps. A kinetically activated braking system is installed on the carriage which prevents secondary impacts to the test specimen.

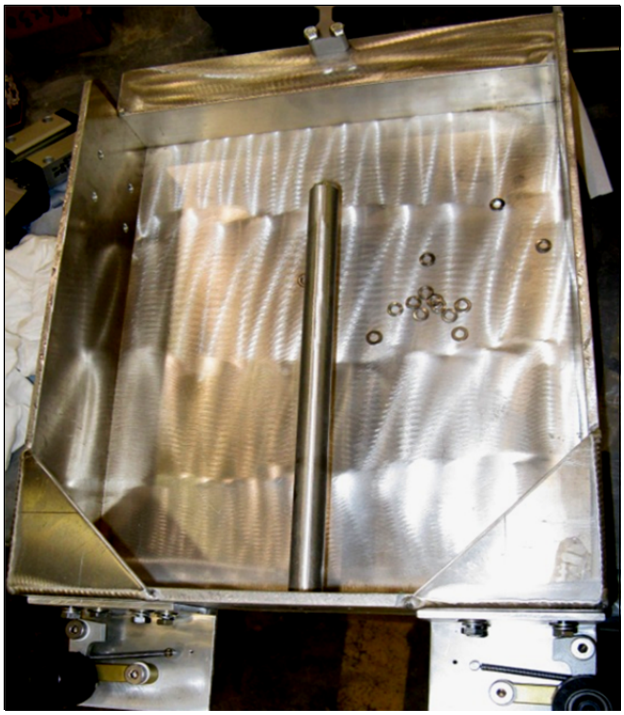
A photo gate sensor timer with the ability to time consecutive events in milliseconds provides the time measurement over a 25.4mm (1.0 in.) range, which is used to compute the velocity at the time of impact. The stop time is triggered when the impactor reaches 0.25 inches from the strike point of the specimen. The deflection of the panel, due to the impact event, is measured via a deflection gauge that is positioned within the well of the concrete base, while the penetration depth of the tup into the panel is measured by a friction collar attached to the tup, as shown in Figure 9c.

The test frame has a drop height range of 0.91 to 3.2 m (3.0 to 10.5 ft). Drop height is established as the distance from the hemispherical strike tip of the tup to the top surface of the test specimen and is read via a calibrated graduated scale on the right vertical channel.

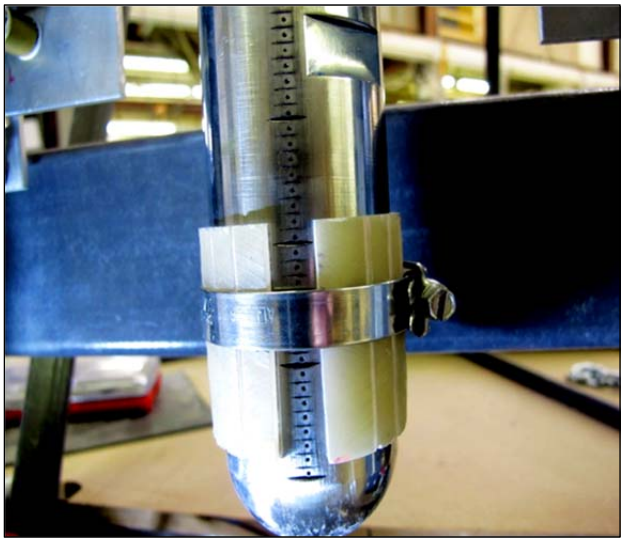
Full details of the design of the impact apparatus and the impact test procedure are documented in Appendix A.



a)



b)



c)

Figure 9: Impact test frame: a) Overall view, b) Impact carriage, c) Tup with depth collar.

2.4 Analysis Plan

2.4.1 Data Acquisition

The large panel flexural tests consisted of static testing of the baseline panels and fatigue testing of the defect panels. Force and load-head position data were recorded by the Instron 8801 control/acquisition software during the large panel flexural tests. While peak and trough data were collected periodically throughout the duration of the fatigue tests, a 10Hz sampling rate was used during the static tests. *(The instrumentation description that follows pertains to the static flexural tests only, since no other instrumentation was used during the fatigue flexural tests.)* Celesco Model SP1 string potentiometers measured vertical displacement at midspan of the specimen. In addition, individual string pots on each end of the panel were used to measure horizontal displacement. Three linear strain gauges were placed on the midline of the panel – one at the panel center and one at the same two locations as the defects on the defect panels. These measurements were used to determine panel stiffness, local strain effects, and ultimate load, which provided values for comparison to model predictions. Strain and string potentiometer data were recorded on a National Instruments LabVIEW SCX1-1001 data acquisition system. Analog force and load-head position output from the Instron was also collected with the LabVIEW system to correlate with the strain and string potentiometer data.

Force and load-head position data were recorded during the C273 foam core shear tests by the Instron 8801 control/acquisition software. The relative displacement of the steel load plates of the C273 specimen, as measured by the LVDTs, was recorded on a National Instruments LabVIEW SCX1-1001 data acquisition system. Analog force and load-head position output from the Instron was also collected with the LabVIEW system to correlate with the LVDT data. The data acquisition sample rate varied depending on the applied strain rate. For quasi-static tests, the sample rate was 20 Hz. For the intermediate and slamming rate tests the rates were increased to 1,000 Hz and 2,000 Hz, respectively.

During the high and low temperature testing, the chamber temperature was monitored using a thermocouple reader. Continuous temperature data were also recorded using an Onset HOBO temperature logger.

Force and load-head position data were recorded during the C393 sandwich beam flexure tests by the Instron 8801 control/acquisition software. A Celesco Model SP1 string potentiometer was used to measure specimen mid-span deflection. The string pot signal, and the analog force and load-head position output from the Instron, were collected with a National Instruments LabVIEW SCX1-1001 system. The data acquisition sample rate varied depending on the applied strain rate. For quasi-static tests, the sample rate was 20 Hz. For the intermediate and slamming rate tests, the rates were increased to 2,500 Hz and 5,000 Hz, respectively. Temperature chamber monitoring was performed in the same manner as it was for the C273 tests.

For the impact testing, data was recorded manually onto HDC form 10.03.2 from the various electronic and mechanical indicators that are part of the impactor test frame. (Complete details of the impactor design are presented in Appendix A.)

The data collected on HDC form 10.03.2 included the following:

1. Specimen ID
2. Test date
3. Air temperature
4. Barometric pressure
5. Humidity
6. Width of test coupon

7. Length of test coupon
8. Thickness of test coupon
9. Drop height of impactor
10. Optical gate time
11. Carriage weight
12. Damage in the 0 degree direction
13. Damage in the 90 degree direction
14. Damage to the bottom skin of test coupon
15. Full downward impactor travel from top surface of static test coupon
16. Panel deflection from bottom skin of static test coupon to bottom skin of coupon acted on by full impact energy.

In addition, photographs were taken of each sample including damage to the bottom skin if applicable. In some select cases the coupon was cut in two (through the impact area) using a band saw in order to observe and record the interior damage to the coupon.

2.4.2 Statistical Methods

The data reduction employed for computing the results for all the tests performed in this study consisted of computing the mean, the standard deviation, and the coefficient of variation (COV) for the specimens in each data set. The COV is calculated as the standard deviation of the data set divided by the mean value of the data set.

During the C273 testing, when the COV was considered too large (usually over 9%) an attempt was made to find outliers in the data using ASTM E178 *Standard Practice for Dealing with Outlying Observations*[22] (E178). Upon review of the values, it was usually found that there was one doubtful value, either the highest or lowest value. The Recommended Criteria for Single Samples was then used to test if that value was an outlier or not. Using this criterion, a test statistic was calculated using the following formulas:

$$\text{Largest value outlier: } T_N = \frac{x_N - \overline{x}}{s} \qquad \text{Smallest value outlier: } T_1 = \frac{\overline{x} - x_1}{s} \qquad \textbf{(1)}$$

where:

T is the test statistic

x is the doubtful value

$\bar{x}$ is the mean value of the property

s is the sample standard deviation

This test statistic is then compared to a table provided in the E178 standard using a significance level. A five percent, one-sided significance level was used for the C273 tests.

Some data sets required the use of other criteria described in the standard for two or more outlying observations. These criteria can be found in the E178 standard. When an outlier was identified through statistical methods, or testing observations, the data from that test was excluded from the calculations of the results.

3 Discussion

3.1 Nondestructive Testing Evaluation

3.1.1 Large Panel Fabrication

Table 7 lists the resins and hardeners that were used to infuse the test panels. The panels constructed with E-glass fabric facings used vinyl ester resin, while the carbon and carbon/aramid hybrid facings used epoxy resin. Infusion data sheets are available in Appendix D.

Table 7: Infusion resins for sandwich panel fabrication.

Resin Type	Manufacturer	Resin	Hardener	Ratio by Wt.
Vinyl Ester	CCP	Epovia RF1001L-00	ARA Luperox DDM-9	100:1.5
Epoxy	Pro-Set	LV117-1	237-1	100:30

Table 8 lists the fabrics that were used to form the skins of the sandwich panels. Table 9 lists the foam core materials that were used in the sandwich panels. For infusion purposes, the foam core material included 1.59 mm (0.0625 in.) diameter perforations (through the thickness) spaced 25.4 mm (1.0 in.) apart in the Corecell foam and 19.1 mm (0.75 in.) apart in the Divinycell foam.

Table 8: Reinforcement fabrics for sandwich panel construction.

Material ID	Fabric Type	Manufacturer	Architecture	Areal Wt. *gm/m^2 (oz/yd^2)*	Dry Thick *mm (in.)*
E-LTM 1603	E-glass	Vector Ply	0/90°	643 (18.96)	0.69 (0.027)
E-LTCFM 2415	E-glass	Vector Ply	0/90°	1263 (37.24)	1.68 (0.066)
E-LTCFM 3610	E-glass	Vector Ply	0/90°	1540 (45.42)	1.42 (0.056)
M8635 CFM	E-glass	Owens Corning	random	450 (13.5)	-
Finishmat D7760	E-glass	Lantor	random	60.0 (1.77)	0.30
C-LA 1812	Carbon	Vector Ply	0°	637 (18.8)	0.99 (0.039)
C-BX 1800	Carbon	Vector Ply	± 45°	580 (17.11)	0.89 (0.035)
C-BX 1200	Carbon	Vector Ply	± 45°	400 (11.80)	0.61 (0.024)
C-LT 1800	Carbon	Vector Ply	0/90°	630 (18.58)	0.89 (0.035)
K-BXM 1308	Aramid	Vector Ply	± 45°	747 (22.02)	-
Material specifications are available in the data sheets found in Appendix B					

Table 9: Foam core materials for sandwich panel construction.

Material	Manufacturer	Nomenclature	Nominal Density *kg/m^3 (lb/ft^3)*
PVC	Diab (Divinycell)	H130	130 (8.1)
PVC	Diab (Divinycell)	H100	100 (6.3)
SAN	Gurit (Corecell)	M100	107.5 (6.7)
SAN	Gurit (Corecell)	M80	85 (5.3)

The Divinycell H Grade Core lists a typical density variation of ±10%. This means that H130 foam core material has a density between 117 and 143 kg/m^3 (7.29 and 8.91 pcf) and the H100 foam core material has a density between 90 and 110 kg/m^3 (5.67 and 6.93 pcf). The Corecell M-foam density variation for the M80 foam core is ±4.7% (81-89 kg/m^3) and for the M100 foam core is ±7.0% (100-115 kg/m^3). The variation in density within a provided foam core material could affect the testing through increased variability in the results.

Table 10 provides the layup schedule for the five sandwich panel types. Plies were numbered starting from the mold side. Defect location through the panel depth is denoted by the colored lines between plies. Each panel contained a defect at only one location through the panel depth, so each colored line represents an individual panel, for a total of 20 panels with defects.

Table 10: Sandwich panel laminate schedules.

Ply #	Sandwich Construction Type				
	1	2	3	4	5
12 (bag)	E-LTM 1603				
11	E-LTCFM 2415		C-BX 1200		
10	E-LTCFM 3610		C-LA 1812		
9	E-LTCFM 3610		C-BX 1200		
8	H130 (38.1 mm)	E-LTM 1603	M100 (25.4 mm)	C-BX 1200	C-BX 1200
7	M8635 CFM	E-LTCFM 3610	M8635 CFM	C-LA 1812	C-LT 1800
6	H130 (38.1 mm)	E-LTCFM 3610	M100 (25.4 mm)	C-BX 1200	M80 (38.1 mm)
5	E-LTCFM 3610	H100 (38.1 mm)	C-BX 1800	M80 (25.4 mm)	M8635 CFM
4	E-LTCFM 3610	E-LTCFM 3610	C-LA 1812	C-BX 1200	K-BXM 1308
3	E-LTCFM 2415	E-LTCFM 3610	C-BX 1800	C-LA 1812	K-BXM 1308
2	E-LTM 1603	E-LTM 1603	K-BXM 1308	C-BX 1800	K-BXM 1308
1 (mold)	M8635 CFM	M8635 CFM	E-Veil	E-Veil	E-Veil
Defect Location	Bag-side w/in Skin	Bag-side Skin/Core	Mold-side w/in Skin	Mold-side Skin/Core	
Specimen ID:	# - B - S	# - B - C	# - M - S	# - M - C	

A total of 30 large panels were fabricated as listed in Table 1. Two panels of each panel type were fabricated without engineered defects and labeled as 1-B-1, 1-B-2… 5-B-2 for baseline testing. The remaining panels were fabricated with defects placed within the skin or at the skin-core interface. The following system was used to label these panels:

 # - S - P,

where

# = Sandwich construction type (*1, 2…5*)
S = Side of core where defect is placed (*M* for mold, or *B* for bag)
P = Placement of defect (*S* for within skin, or *C* for skin-core interface)

For example, the panel with delaminations on the bag side of Sandwich Type 3 placed at the skin-core interface is labeled as 3-B-C.

Initially, delaminations were simulated by joining two plies of 0.025 mm (0.001 in.) of Teflon sheet around the perimeter of the defect with a narrow strip of roller glue adhesive. This method produced a clear delamination by preventing resin from entering the interface between the two layers of Teflon. While one ply of Teflon would result in a very weak bond to the resin on either side and effectively simulate a delamination under mechanical loading, intimate contact would likely cause the defects to register differently when inspected by the various NDT techniques. Defect shapes were cut on a water jet by placing several layers of Teflon film between sacrificial plates. Sample delaminations are presented in Figure 10.

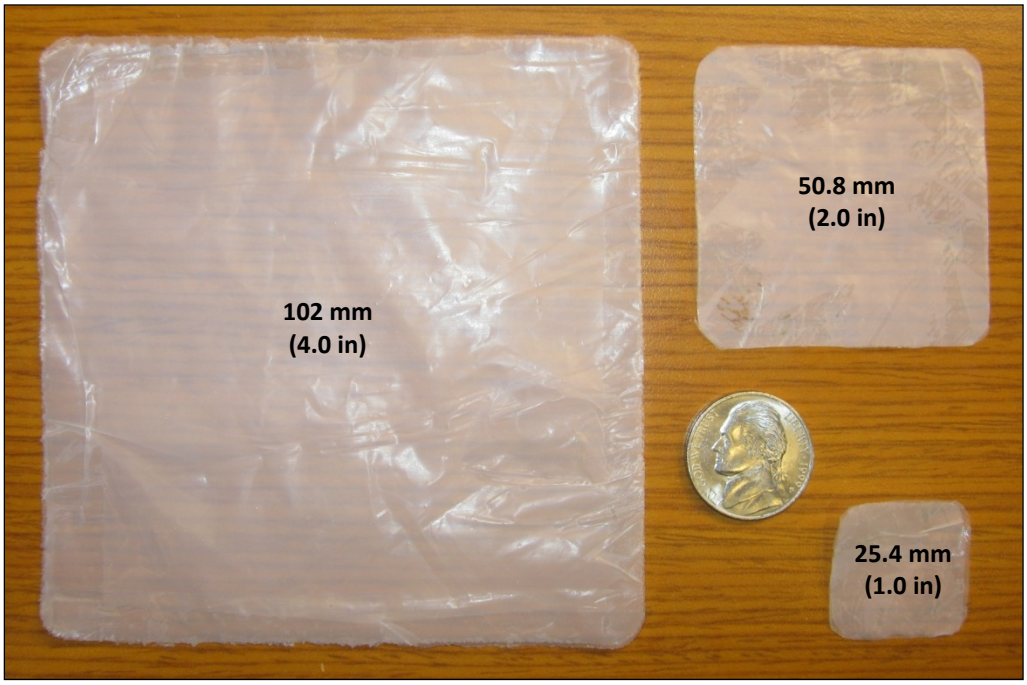


Figure 10: Sample Teflon delamination inserts.

Subsequent inspection of the first batch of NDT panels appeared to indicate that the inserts were bonded into the panel. Delaminations were identified using UT, but thermography and shearography methods did not result in flaw indications. Therefore, a trial panel was fabricated using various alternatives to simulate delaminations. The final method selected to produce the engineered defects was to hot laminate a piece of paper. Slightly undersized defects were cut to size and shape from 0.107mm (0.0042 in.) thick bond paper and inserted between 0.076 mm (0.003 in.) thick polyester lamination sheets and processed through a hot laminator. Once laminated, the defects were trimmed leaving approximately 3.0 mm (0.13 in.) of lamination around the outer edge of the paper to produce the intended size and to prevent any resin from infiltrating the assembly.

Three defect sizes were chosen and inserted into the large panels: 25.4, 50.8, and 101.6 mm (1.0, 2.0, and 4.0 in.) squares (Figure 11). The corners of each engineered defect have a 6.4 mm (0.25 in.) fillet, since actual delaminations rarely have sharp corners and mode separation is well defined in the numerical model at a rounded corner. Defect placement was selected in order to match the relative magnitude of the shear and moment induced stresses within a simply supported panel under four-point loading (test configuration) to the maximum stresses in a panel with fixed ends and uniform loading (similar to hull structure). Shear and moment diagrams are presented in

Figures 12 and 13, respectively, for an arbitrary 2.72 kPa load per mm (10 psi load per inch) of panel width. At a distance of 287 mm (11.3 in.) from either support line, both the shear and moment magnitudes in the simply supported panel match the values at the ends of the clamped-support panel as indicated by the diamond markers. By positioning the load lines at quarter-point loading, the moment between load points is reduced to minimize damage away from the defects while a reasonable distance is maintained from the edge of the simulated delamination to the load pad (92.1 mm (3.63 in.) minimum).

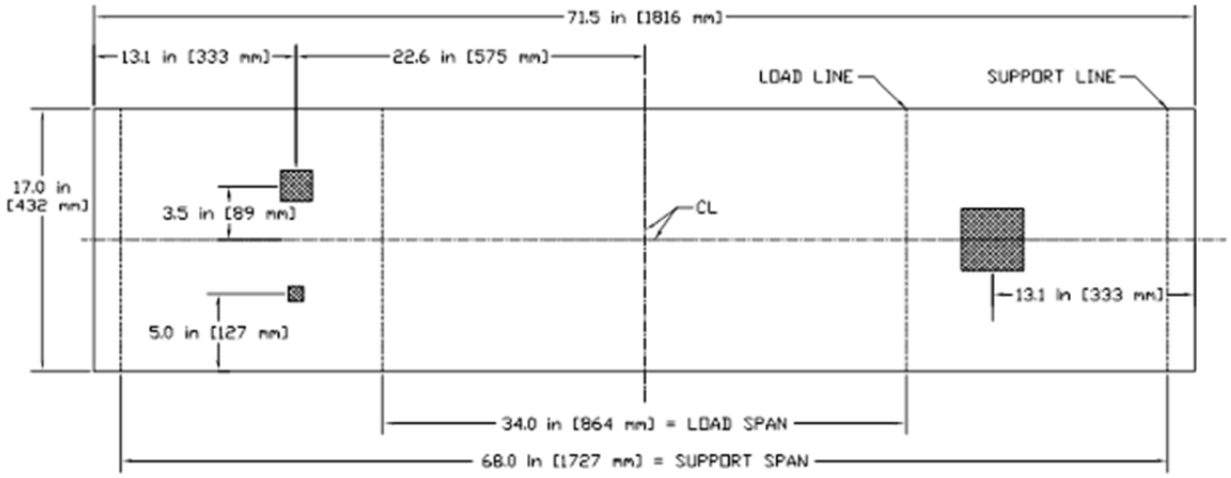


Figure 11: Large panel dimensions and defect arrangement.

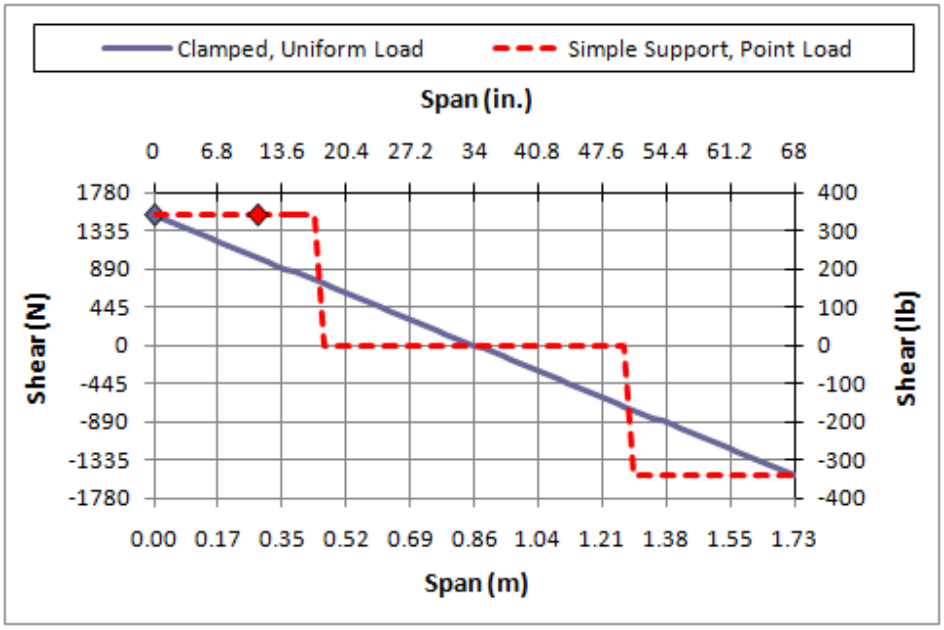


Figure 12: Large panel shear diagrams, $V(x)$.

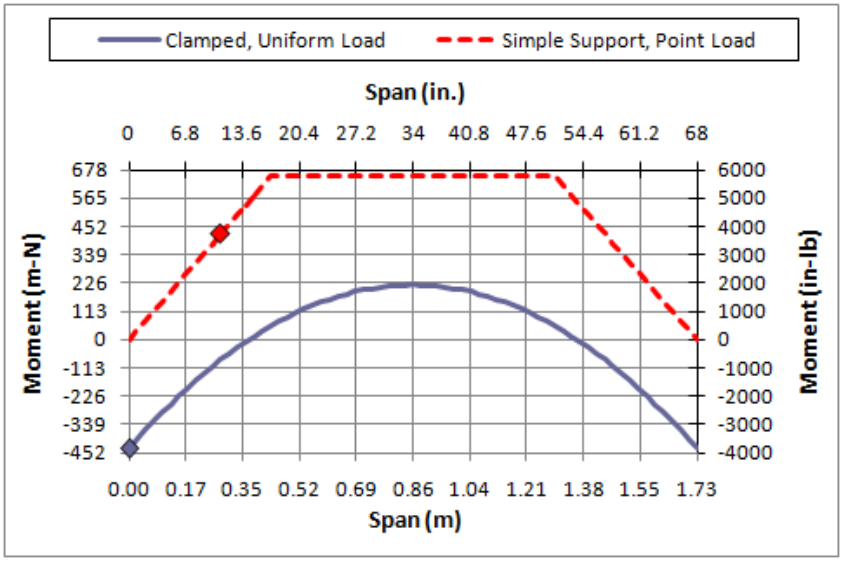


Figure 13: Large panel moment diagrams, M(x).

3.1.2 Large Panel Inspections

Prior to conducting structural tests, each panel was inspected using thermography, shearography, UT and SIDER. The ability of each method to accurately identify the size and location of engineered delaminations was compared as a function of physical factors including defect depth and size, surface texture, and skin material. In addition, the time required to set up and inspect each panel was also compared. A summary of the results from the panel inspections are presented in Table 11.

Table 11: Large panel NDT inspection results summary.

Defect Type	NDE Method					
	UT Inspection	Infrared Thermography	Laser Shearography			SIDER
	A-Scan	*Flash-Heating*	*Heat Load*	*Vacuum Load*	*Heat and Vacuum*	
Crack	C	N	B	B	B	C
Voids/Porosity	C	B	A	B	A	N
Delamination in skin *Small (1-2 in.)*	A	C	B	B	A	C
Delamination in skin *Large (4 in.)*	A	C	B	B	A	C
Delam. at skin/core interface *Small (1-2 in.)*	B	N	C	C	B	C
Delam. at skin/core interface *Large (4 in.)*	B	N	C	C	B	C

A = **High** *(best/optimal)* **C** = **Limited** *(may work under certain conditions only)*

B = **Average** *(works generally well)* **N** = **Not Applicable** *(will not detect the defect)*

3.1.2.1 Thermography

Inspection with the FLIR IR camera system proved to be quite difficult to achieve definitive defect images. The camera and computer were set up as shown in Figure 14. Initial attempts were made by heating an area of the panel within the defect region with a heat lamp and analyzing the image during both the heat up and cool down processes. The results received using this technique proved to be indistinct. Further attempts were made while trying different heat sources including a heat gun, garage heater, and pre-heating the panels in a kiln. These techniques proved ineffective. Some success was had locating defects simulated with laminated sheets of paper within a defect trial panel so defect type could be a limiting factor to the success of the infrared inspection.



Figure 14: FLIR IR camera setup.

3.1.2.2 Shearography

Inspection with the shearography system was quite easy and the results were promising. Initial inspections did not show defects very well using the Q-800 tripod system and thermal loading using a heat lamp. The Q-810 vacuum system also missed most of the defects when using vacuum as the means of loading the panel. It was determined that applying a brief heat load (5-10 seconds) before attaching the Q-810 unit, produced greatly improved results. The Q-810 has no issues with stability as it is vacuum sealed to the inspection surface. One issue with the stand alone Q-800 is any movement between the camera and the inspection surface creates insurmountable amounts of noise in the image and greatly affects the ability to perceive defects. Using the vacuum attachment hood also eliminates noise caused by stray thermal effects such as wind and sunlight. The optimum test method after many different combinations is:

- Heat the inspection surface for 5-10 seconds.
- Attach the Q-810 hood and turn on vacuum.
- Refresh image after 15 seconds, defect should appear within the next 30 seconds.

This method worked well for most of the panels, with some of the thicker laminates needing additional heat to achieve acceptable results. Figure 15 shows the test setup and the results are presented in Table 12

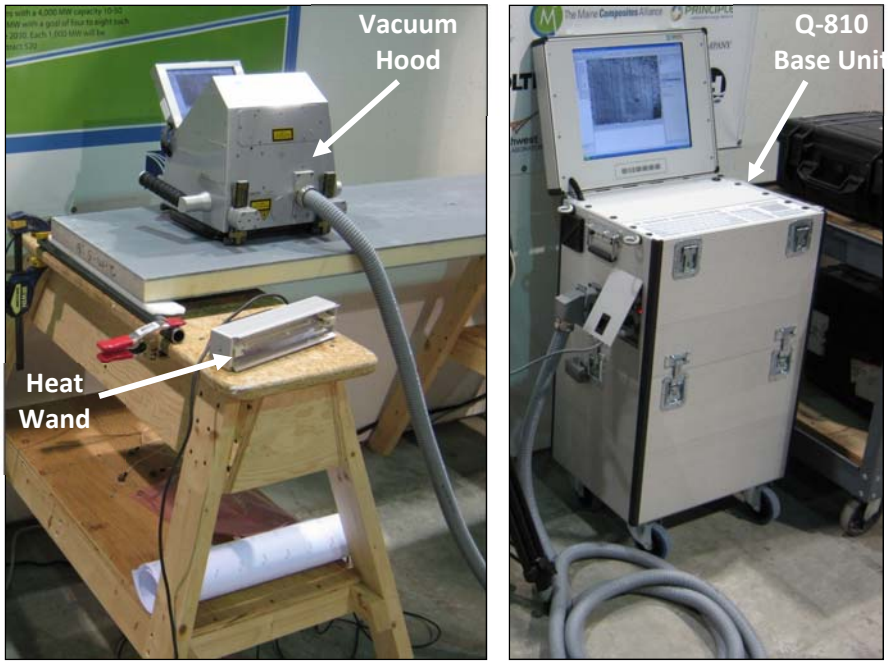
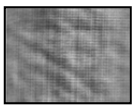
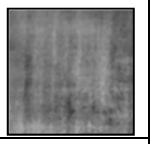
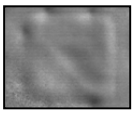
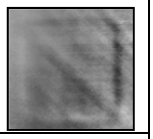
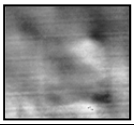
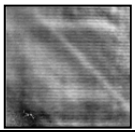
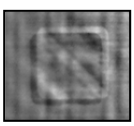
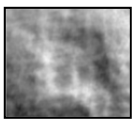


Figure 15: Q-810 Shearography system setup.

Table 12: Shearography results.

	Skin Defect		Core/Skin Interface Defect	
Sandwich Construction Type	***Ease and Clarity of Detection***	***Example***	***Ease and Clarity of Detection***	***Example***
1	Good		Poor	
2	Good		Fair	
3	Good		Good	
4	Fair		Fair	
5	Good		Fair	

3.1.2.3 Ultrasonic Inspection

Ultrasonic inspection was successful on all defect sizes and panel layups. The 25.4 mm (1 in.) 1 MHz probe was used for all of the E-glass panels, with an example of the signal and equipment settings shown in Figure 16. The smaller 12.7 mm (0.5 in.) 2 MHz probe was found to work better on the thinner carbon panels. It was slightly more difficult to inspect the bag side of the panel due to the roughness of this surface, but with a little extra couplant a good signal was achieved. UT was performed both before and after fatigue testing the panels.

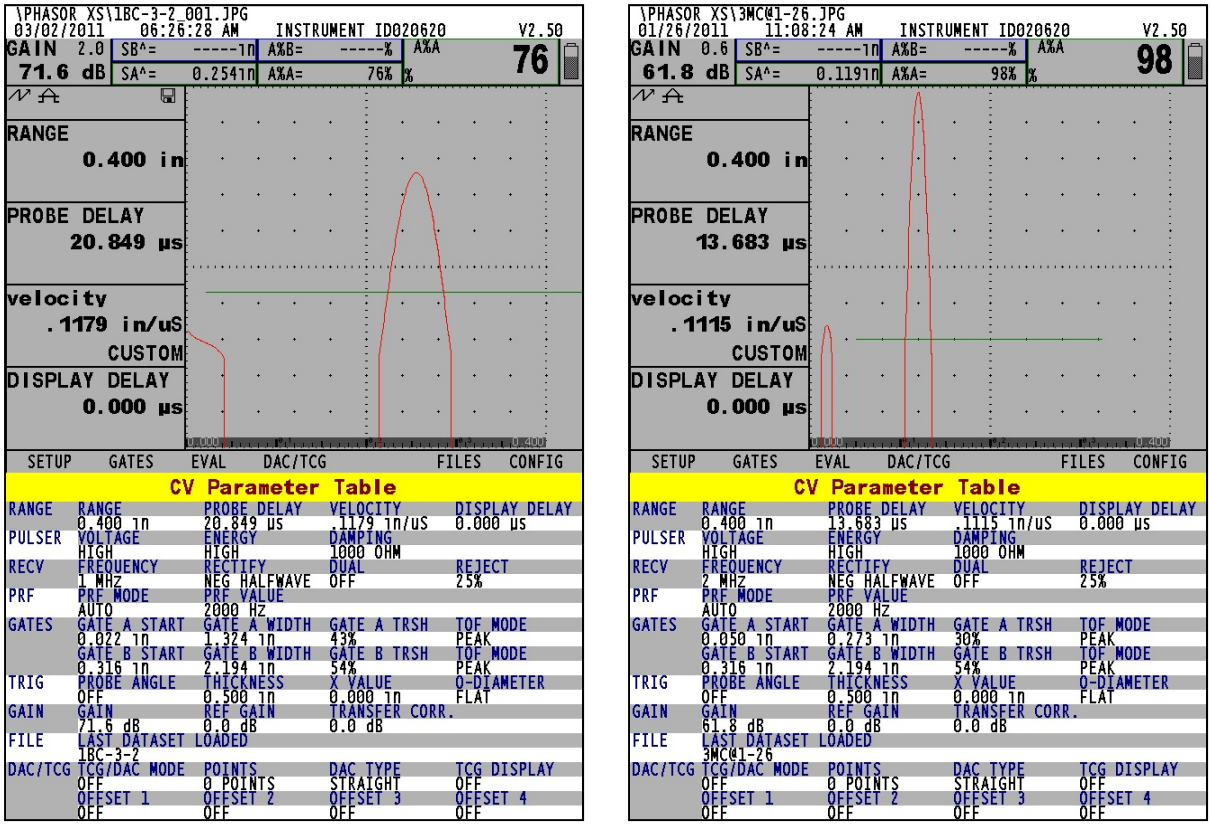


Figure 16: Example of signals and settings for both probes: 25.4mm (left), 12.7mm (right).

3.1.2.4 SIDER Analysis

SIDER testing was performed on each defect panel taking approximately two hours to evaluate each panel. Analysis of the heavy laminates proceeded faster – closer to one hour and twenty minutes – since good coherence was easily achieved and repeat hits were very few. Lighter laminates (at least for the given boundary conditions) required more repeat hits with the impact hammer. Each panel was mapped with 324 evenly spaced tap points and three accelerometers using a paper template. The end conditions consisted of a 25.4mm (1 in.) diameter steel pipe flush with the end of the panel and a 12.7 mm (0.5 in.) foam pad running the length of the pipe between the panel and the pipe. Panel type 4 proved to be too light to get good coherence using these end conditions, so the ends of the panel were rigidly clamped. Each point was tapped three times and averaged. This step was repeated for each point. If any of the three hits showed bad coherence, the data was discarded and that point was repeated.

The process for analyzing tap-test data using the SIDER routine is outlined below.

- Measure transfer functions (accelerance) from each tap point to each accelerometer, which is proportional to operating deflection shape (ODS);
- At each location and frequency, compute operating curvature shapes (OCS) using a second order centered finite difference (points along the edges use a shifted finite difference approximation);
- At each location and frequency, compute a cubic polynomial fit of the modal curvature using the Band Gapped Smoothing Method (BGSM) – in this approach, the point in question is omitted from the curve fit and the two points to either side are used to determine the polynomial coefficients;
- Perform the two previous steps for each analysis direction (rectilinear grid lines running in the long and short dimensions) and separately for real and imaginary components;
- At each location and frequency, calculate a single damage index by summing the squared error between the curve fit and the measured data for the real and imaginary values;
- Apply a weighting function to zero the damage indices for tap locations within two gird points of an accelerometer to remove local effects on curvature;
- At each location, average the damage indices across all frequencies and plot the results on a color surface plot.

Personnel from the Naval Surface Warfare Center Carderock Division (NSWCCD) were asked to process some of the data acquired at AEWC using the code developed by Crane and Ratcliffe [16]. The intent was to compare output from their validated Visual Basic code with the output generated by the MATLAB code written at AEWC. Discussions with NSWCCD indicate similar results. Both codes indicated unexpected results when processing along the short panel dimension – very high damage indices with an apparent "shift" in the surface plot. This may be attributed to switching operators or stopping data acquisition at the end of a row. Damage index magnitudes calculated along the long dimension of the panel matched expectations and did not show any clear indications, other than the influence of the accelerometers.

During discussions with R. Crane, he indicated that flaws as small as one-half the grid spacing have been found using SIDER. For example, the grid spacing of 2 in. by 2 in. used in this test program could possibly have identified defects as small as 1 in. However, the nature of the engineered defects does not appear to have degraded the stiffness of the panels significantly enough to impact the local curvature. In addition, NSWCCD and AEWC noticed relatively high noise levels in the raw data when processing the mode shapes that are likely influencing the quality of the processed images making indications more difficult to observe. Noise levels will be dependent on instrumentation quality and setup, as well as the chosen boundary conditions. Previous testing by Crane and Ratcliffe has shown that test panels, especially with free-edge boundary conditions, are more difficult to obtain quality data from than panels with "fixed" boundary conditions like those that exist as a subcomponent of a larger continuous structure.

3.1.3 Large Panel Fatigue and Static Tests

Static tests were conducted on the baseline panels for each sandwich construction type. The ultimate load resisted by the baseline panel was used as a target for determining the fatigue load amplitudes and as a reference value for computing residual strength for the panels with engineered defects. All panels were post-cured at 60.0-65.6°C (140–150°F) for 12 hours prior to testing [23]. Tests were conducted using a 250kN (56.2 kip) actuator and a fatigue rated load fixture presented in Figure 17.

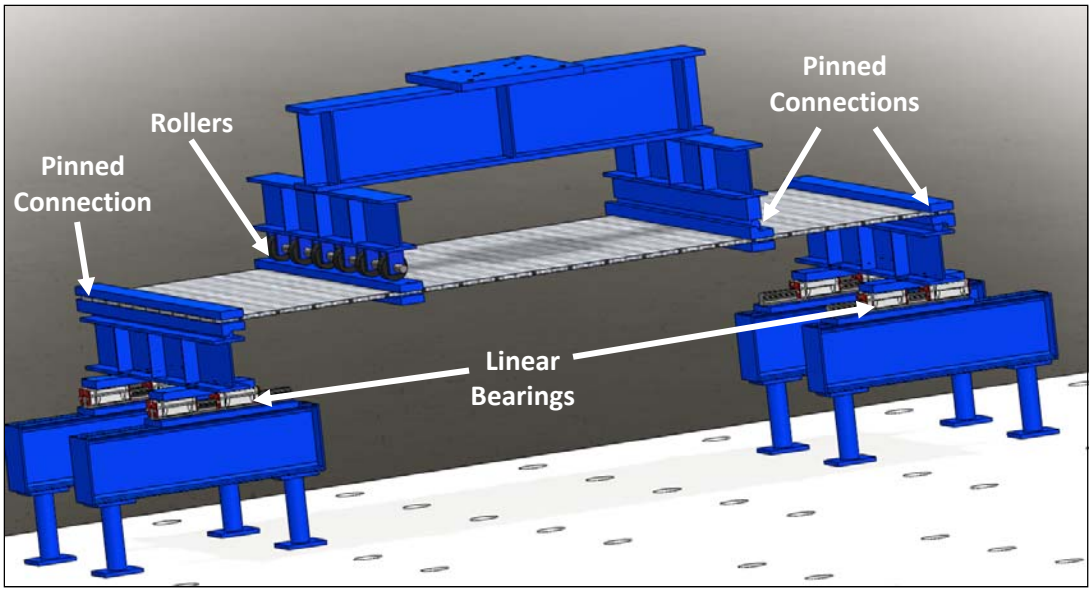


Figure 17: Static and fatigue large panel test fixture.

As discussed in Section 3.1.1, a four-point loading configuration was selected for the static and fatigue tests. The panel supports were designed to provide simple support conditions during the tests. They allow free rotation and translation through the use of a pivot and linear bearing assembly. The load was applied at two locations, positioned a distance from each end support equal to a quarter of the total support span. The load beams also allowed rotation at both points and translation at one point using rollers. The fixture was designed to handle panels up to 1.2m by 2.4m (4ft by 8ft) and rated for fatigue loading. Static testing results are presented in Table 13.

Table 13: Large panel static test results.

Panel ID	Max Load	Max Deflection	Panel Failure Mode & Location	Stiffness	
				Measured	***Predicted***
	kN (kips)	*mm (in.)*		*kN-mm^2 x10^6 (lb-in^2 x10^6)*	
1-B-1	140.9 (31.67)	102.9 (4.053)	Compression under roller load point	125.1 (43.58)	122.0 (42.52)
1-B-2	136.3 (30.63)	101.6 (4.001)	Compression under roller load point	120.9 (42.12)	122.0 (42.52)
2-B-1	52.75 (11.86)	160.2 (6.309)	Compression under roller load point	27.54 (9.596)	24.96 (8.699)
2-B-2	55.46 (12.47)	169.7 (6.681)	Compression under roller load point	28.07 (9.782)	24.96 (8.699)
3-B-1	46.19 (10.38)	77.17 (3.038)	Compression under both load points	46.75 (16.29)	46.85 (16.32)
3-B-2	42.46 (9.545)	71.21 (2.804)	Compression under roller load point	45.92 (16.00)	46.85 (16.32)
4-B-1	15.48 (3.480)	100.1 (3.940)	Compression under roller load point	11.42 (3.978)	11.12 (3.874)
4-B-2	15.62 (3.512)	100.7 (3.964)	Compression under roller with local skin buckling	11.78 (4.103)	11.12 (3.874)
5-B-1	20.27 (4.558)	76.67 (3.018)	Compression at midspan	19.42 (6.765)	18.63 (6.493)
5-B-2	22.50 (5.059)	87.87 (3.459)	Compression under pinned load point	18.97 (6.611)	18.63 (6.493)

Prior to conducting fatigue loading on the panels with engineered defects, a load spectrum needed to be defined. Variable amplitude fatigue loading applied as numerous constant amplitude blocks was selected to simulate the distribution of higher-probability, low-amplitude cycles with lower-probability, high-amplitude cycles. One-year and five-year spectra normalized to the maximum applied fatigue stress level are shown in Figures 18 and 19[24]. These histograms were combined (one five-year plus 25 one-year) to build a load histogram simulating a 30-year life load spectrum.

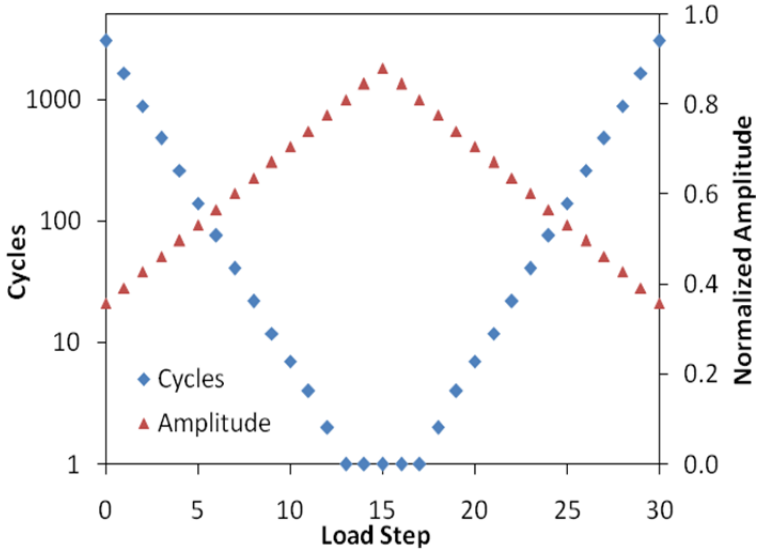


Figure 18: One-year fatigue spectra.

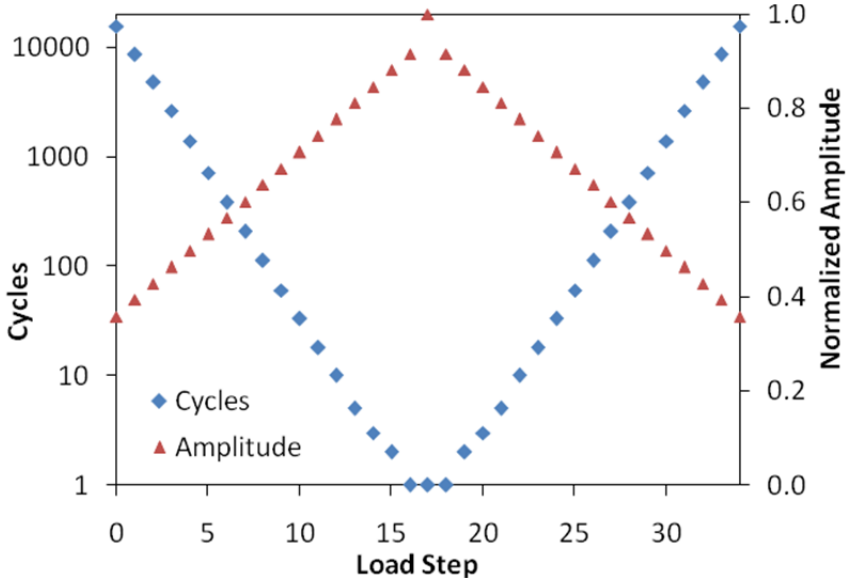


Figure 19: Five-year fatigue spectra.

Once the normalized load spectra were defined, an appropriate scale factor needed to be determined. Based on constant amplitude fatigue life data (R = 0.1), a 30-year safe damage limit was previously calculated for an E-glass/vinyl ester laminate as 54% of the B-basis value ultimate tensile strength [24]. Also, testing performed at Virginia Tech indicated a safe damage limit for a 30-year design life to be 44% of the static tensile strength[5]. These studies were based on fully reversed fatigue testing (R = -1) of E-glass/vinyl ester laminates. American Bureau of Shipping

(ABS) suggests a fatigue knockdown factor of 50% for preliminary design in the absence of stress-strain data for E-glass/vinyl ester[23]. For the purposes of evaluating the fatigue life or residual strength of panels in this study, a safe damage limit, or scale factor, of 50% of the undamaged panel ultimate strength has been selected. Table 14 is an excerpt from a spreadsheet used to calculate the one- and five-year load spectra. An ultimate load of 222 kN (50 kips) has been assumed for this example.

Table 14: Sample one- and five-year load spectra (fatigue load spectra – Panel Type 1).

Load Step	1-year Sequence		5-year Sequence	
	Cycles	***Amplitude***	***Cycles***	***Amplitude***
	quantity	*kN (kip)*	*quantity*	*kN (kip)*
1	3044	39.8 (8.95)	15500	39.8 (8.95)
2	1648	43.7 (9.82)	8500	43.7 (9.82)
3	892	47.55 (10.69)	4750	47.55 (10.69)
4	483	51.42 (11.56)	2625	51.42 (11.56)
5	261	55.34 (12.44)	1375	55.34 (12.44)
6	141	59.21 (13.31)	706	59.21 (13.31)
7	76	63.08 (14.18)	382	63.08 (14.18)
8	41	66.95 (15.05)	207	66.95 (15.05)
9	22	70.82 (15.92)	112	70.82 (15.92)
10	12	74.69 (16.79)	60	74.69 (16.79)
11	7	78.56 (17.66)	33	78.56 (17.66)
12	4	82.47 (18.54)	18	82.47 (18.54)
13	2	86.34 (19.41)	10	86.34 (19.41)
14	1	90.21 (20.28)	5	90.21 (20.28)
15	1	94.08 (21.15)	3	94.08 (21.15)
16	1	97.95 (22.02)	2	97.95 (22.02)
17	1	94.08 (21.15)	1	101.8 (22.89)
18	1	90.21 (20.28)	1	111.2 (25.00)
19	2	86.34 (19.41)	1	101.8 (22.89)
20	4	82.47 (18.54)	2	97.95 (22.02)
21	7	78.56 (17.66)	3	94.08 (21.15)
22	12	74.69 (16.79)	5	90.21 (20.28)
23	22	70.82 (15.92)	10	86.34 (19.41)
24	41	66.95 (15.05)	18	82.47 (18.54)
25	76	63.08 (14.18)	33	78.56 (17.66)
26	141	59.21 (13.31)	60	74.69 (16.79)
27	261	55.34 (12.44)	112	70.82 (15.92)
28	483	51.42 (11.56)	207	66.95 (15.05)
29	892	47.55 (10.69)	382	63.08 (14.18)
30	1648	43.7 (9.82)	706	59.21 (13.31)
31	3044	39.8 (8.95)	1375	55.34 (12.44)
32			2625	51.42 (11.56)
33			4750	47.55 (10.69)
34			8500	43.7 (9.82)
35			15500	39.8 (8.95)

Fatigue loads were applied by running the five-year spectra as a break-in period followed by 25 one-year spectra. As a result, 400,354 cycles are in each 30-year block. Fatigue tests were run on each defect panel with the mold side facing down in the test fixture. This placed the bag side in

compression similar to the location of maximum stress at the end of a "fixed" hull panel and applied compression or tension loading in the vicinity of the defects depending on their location relative to the core. Fatigue tests continued until the 30-year load spectrum was complete.

After 30 years of cyclic loading were completed on all test panels no measureable degradation or propagation of defects was measured. Unexpectedly high damage tolerance after completing the 30-year N2C load spectrum (with a knockdown of 0.5) would suggest that a substantial degree of conservatism may be able to be removed from the design guidelines. However, further analysis of the data and the load spectrum was performed after the completion of this phase of the study. The results of this additional testing and analysis are included as an addendum and are presented in Appendix E.

3.1.4 Numerical Modeling of Large Panels

A combined shell/3D FE model has been selected for predicting the response of hull panels with delamination defects subjected to quasi-static loading. The use of shell elements efficiently predicts the necessary global panel behavior with minimal degrees of freedom (DOF) resulting in a less computationally intense analysis. Continuum (3D) elements are required in the region surrounding the delamination front where the accuracy of a full three-dimensional solution is required. Krueger and O'Brien successfully demonstrated the use of this combined approach by modeling fracture coupons used to derive Mode I (double cantilever beam (DCB)), Mode II (end notched flexure (ENF)), and Mixed Mode (single leg bending (SLB)) strain energy release rate (SERR) [27]. The results of their investigation, performed using the ABAQUS geometric nonlinear analysis procedure, concluded that a four-noded S4 type quadrilateral shell element and the eight-noded C3D8I solid element yielded nearly identical results to higher order elements. The C3D8I element includes incompatible (internal deformation) modes in order to eliminate the parasitic shear stresses that occur in bending. The same paper also includes recommendations for the extent of solid elements and a refined mesh area in the vicinity of the delamination front as a function of laminate thickness. Ferrie and Rousseau also provide suggestions regarding element size and mesh extent but as a function of crack length [28]. SERR is calculated by extracting element forces and displacements at the delamination front and performing the VCCT. Results also showed that simple analyses where element penetration was not prevented were almost in exact agreement with results from models that included contact. Thus, complex contact elements could be avoided further reducing computation time.

Since the intent of this model is to evaluate the effect of delaminations in a representative hull panel (substructure) from a larger structural model, a parametric modeling approach is used. Essentially, an input file is generated that includes parametric quantities, equations, and software commands required for model generation, solution, and post-processing. Various scenarios can be readily evaluated by simply modifying a few key variables. In this way, parametric studies can be efficiently conducted to quantify the impact of delamination size, depth, and location relative to panel dimensions, mechanical properties, and loads.

Sandwich construction types 2 and 4 were selected for the numerical study (Table 10). Mechanical tests were conducted to derive the necessary material properties of each lamina for input to the model as well as strength parameters for evaluating failure criteria. In addition, Mode I and Mode II tests were conducted to determine fracture failure criterion at selected interfaces within the skin laminates. When either G_I or G_{II} is very small relative to the other, a single mode criterion is typically appropriate. Otherwise, a mixed mode criterion is suggested. A complete description of the fracture tests conducted and the associated results are provided in Appendix F.

Panel geometry was selected to match the experimental arrangement (Figure 20). Overall panel width is 432 mm (17 in.) and support span is 1727 mm (68 in.). Defect placement is also consistent with experiments.

The ANSYS APDL input file consists of three major sections: pre-processing (model generation), processing (solution), and post-processing (data analysis). Each of these sections is described below, and a sample input file is presented in Appendix G.

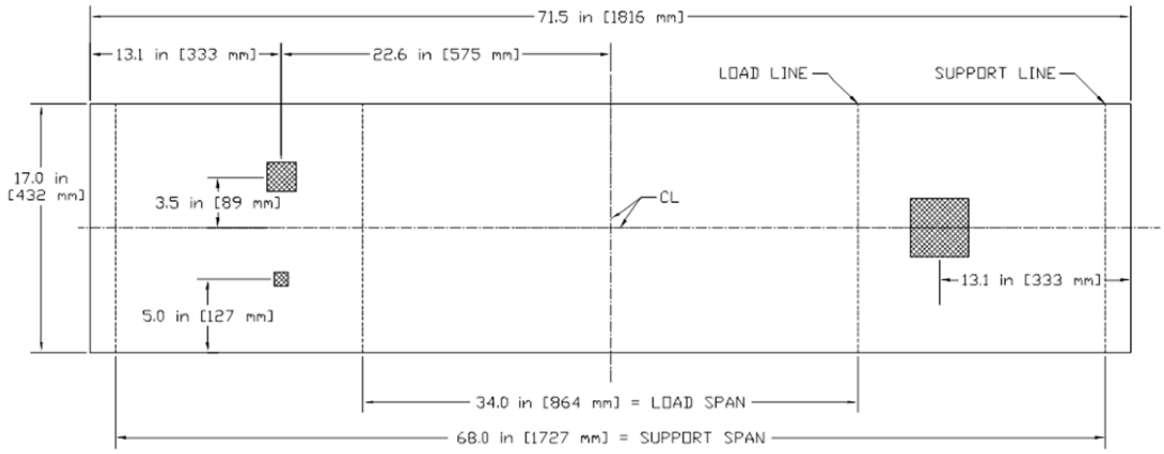


Figure 20: Geometry of the fatigue panel model.

3.1.5 FE Model Pre-processing

Most of the user input occurs at the beginning of the input file. Parameters are established that define geometry and material information required to create the model. These include panel dimensions, defect size and location, number and thickness of plies, material properties, and loads. Wherever possible, other parameters are created from the input variables to minimize the amount of required user-provided information.

Initially, two element types were selected for this analysis. SHELL181 elements were used to represent the majority of the composite panel that exists beyond the defect region. This is a four-node, 3D shell element with six degrees of freedom at each node that supports up to 255 layers. Layer information, such as material number, ply thickness, and ply orientation, are input using section commands. The selected element options are listed below.

- Bending and membrane stiffness (default).
- Full integration with incompatible modes (recommended for layered applications).
- Constitutive thickness-update algorithm (default).
- Data stored for top and bottom of all layers.

SOLID185 elements were used to represent the local region surrounding the delamination. Every ply in the laminate consists of at least one layer of solid elements depending on the element size and ply thickness. Details of the mesh refinement studies and final selected element sizes and extents are presented later in this section. A diagram of the defect region geometry is presented in Figure 21. The selected element options are listed below.

- Enhanced strain formulation to prevent shear locking in bending problems.
- Nonlayered structural solid.
- Mixed *u-P* (displacement-pressure) formulation.

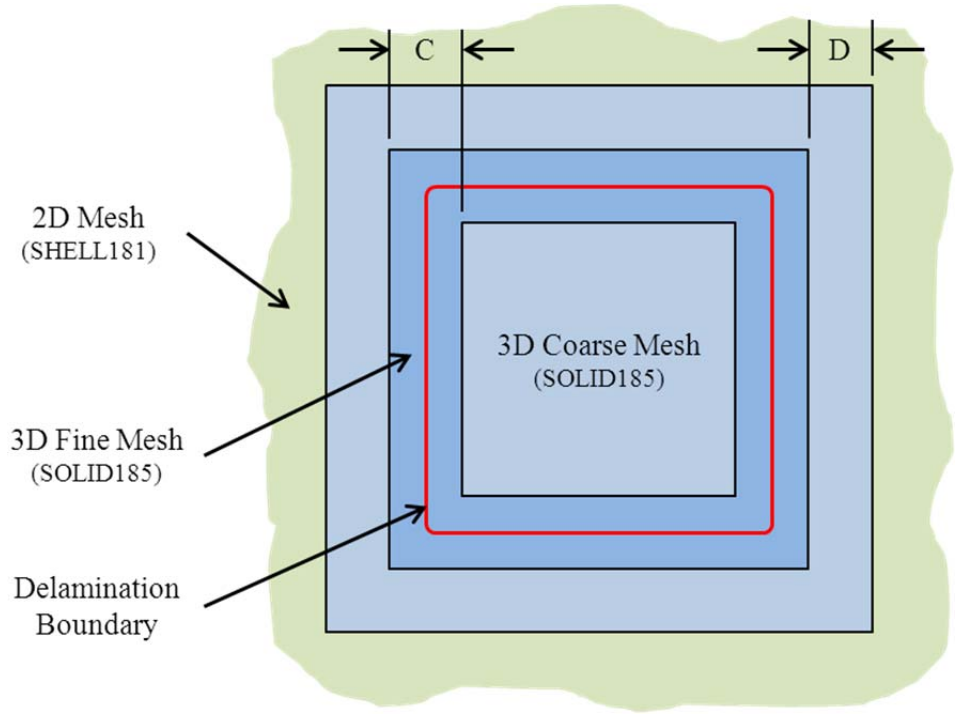


Figure 21: Finite element defect region mesh size and extent.

While it was hoped that contact elements would not be required, initial analyses proved otherwise. Given the panel loading configuration and boundary conditions, the predicted values for G_I (opening mode) should have been essentially zero. G_I values nearly equal to calculated G_{II} values suggested penetration of the upper elements at coincident nodes. The major difference between this model and the ENF and SLB specimens modeled by Krueger and O'Brien is that a delamination contained within a panel does not permit unconstrained sliding like the three free edges near the crack tip of the fracture specimens. Therefore, CONTA178 3D node-to-node contact elements were used to prevent interpenetration of the coincident nodes. The gap size is set to zero and the contact normal is defined as the global *Z* direction. This is the least computationally expensive contact element and applies well to this model given the alignment of the upper and lower meshes at the delamination. The selected element options are listed below.

- Augmented Lagrange method (penalty method with penetration control).
- Unilateral contact behavior (normal pressure is zero if separation occurs).

Model geometry is based on key input parameter definitions including panel length/width, delamination length/width, location and depth of delamination, and the number and thickness of lamina. The code uses these inputs to generate volumes in the defect region corresponding to the coarse mesh, fine mesh, and delamination boundaries. These volumes are then glued together, with the exception of the interface immediately above and below the delamination, so that adjacent volumes will share the same nodes when meshed. The volume that straddles the mid-plane of the laminate stack is split into two volumes along the mid-plane. This ensures that the shell elements will cleanly mesh with the solid elements. Finally, the area representing the remainder of the panel is constructed around the solid elements. In this analysis, the area is subsequently split along two load lines corresponding to the four-point bend test configuration. Future applications of this model are expected to employ a pressure loading over the entire panel, which would not require dividing the global plate area. Model geometry is shown in Figure 20

The next section of the code defines and builds the finite element mesh. All solids are meshed with hexagonal elements and shells are meshed using quadrilateral elements. The extent of the fine mesh region is defined by the parameter *C*. The element size in this region, *del_F*, largely affects the accuracy of the VCCT calculations. Initial values for *C* and *del_F* were 3 mm (0.118 in.) and 0.25 mm (.0098 in.), respectively. Consequently, this combination results in six elements on each side of the delamination front regardless of defect size. The coarse mesh regions internal and external to the fine mesh region are controlled by the coarse element size *del_C*. The extent of the coarse region outside the delamination area is defined by the parameter *D*. Initial values for *D* and *del_C* were 11 mm (0.433 in.) and 2.2 mm (0.087 in.), respectively for a total of five elements. The ability to control the 3D element size in the thickness direction is provided by the parameter *del_Z*, which was initially set at 2 mm (0.079 in.). The shell element mesh size is set using the parameter *del_S*, which was started at 8 mm (0.315 in.).

More than 20 models were evaluated to determine the preferred mesh configuration for this analysis [Appendix G]. First, shell mesh size was varied, then through-thickness mesh size, followed by defect region mesh size and extent. Table 15 lists the final selected mesh refinement.

Table 15: Mesh refinement parameters.

del_S	***del_Z***	***del_F***	***C***	**Number of Elements**	***del_C***	***D***	**Number of Elements**
(mm)	(mm)	(mm)	(mm)		(mm)	(mm)	
10.0	5.0	0.5	5.0	10	2.0	6.0	3

Once the mesh controls, material properties, and element types were assigned to the geometric elements, the FE mesh was automatically generated by the software. Built-in checking routines warn the user if any elements violate shape limits. An example of the resulting mesh is shown in Figure 22 for a 51 mm (2.0 in.) delamination in sandwich construction type 2.

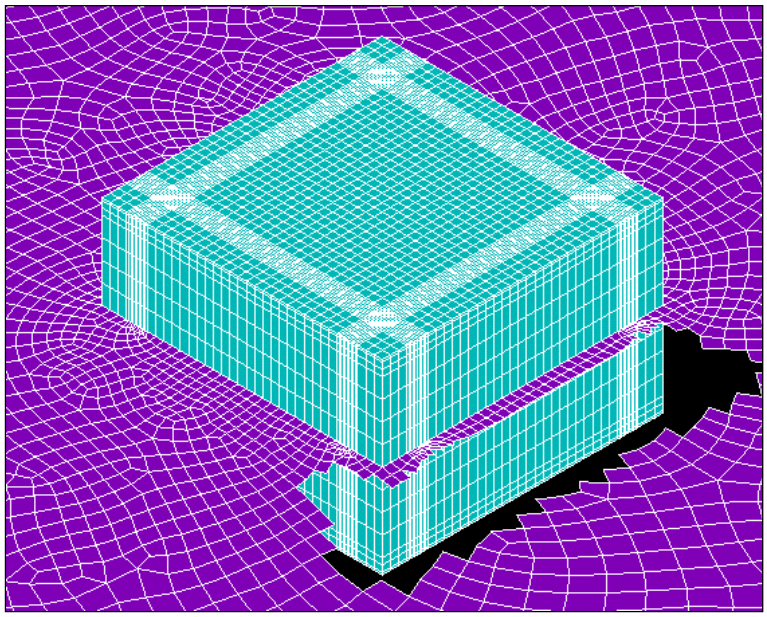


Figure 22: Sample mesh – 51 mm (2.0 in.) delamination *(shell elements omitted for clarity).*

The use of shell and solid elements requires the application of constraints at the interface to provide kinematic compatibility, i.e. 2D elements have six DOF at each node but 3D elements have only three translational DOF at each node. The common node at the shell/solid interface is selected as the master node. All nodes directly above and below that node are the corresponding slave nodes. Constraint equations are automatically generated using the CERIG command to ensure that moments are transferred and the face of the solid element stack remains plane. This process is repeated for all nodes around the perimeter of the delamination.

The last step prior to applying boundary conditions and loads involves generating contact elements between the upper and lower delamination surfaces. These elements are generated automatically using the EINTF command, which couples coincident nodes along a defined normal direction. Contact stiffness is calculated based on the elastic modulus of the materials in contact and the nodal area. Otherwise, the pressure between the surfaces is zero when a gap exists. The panel loading arrangement would suggest that G_I should be close or equal to zero – the configuration is principally similar to a Mode II test. Without the contact elements, mode mixity was spuriously around 45–50% due to interpenetration of the coincident nodes. Applying contact elements resulted in generally small G_I contribution to total SERR.

Boundary conditions in the model have been selected to match the four-point bend test configuration. The panel supports are restrained along the edge only in the vertical (Z) direction to replicate the pin connections mounted on linear bearings. The outer node on one side of each support line is also restrained in the transverse (Y) direction. The left load line is restrained in the longitudinal (X) direction similar to the test arrangement. The loads are applied at each node and the magnitude is determined by dividing the input force at each load point by the number of nodes across the width of the panel.

3.1.6 FE Model Processing

A static analysis is performed based on geometrically linear (small deformation) assumptions. A nonlinear solution is required since the contact elements require an iterative approach to achieve convergence. Most model solutions converged within two to four iterations and, depending on defect size, required about five to ten minutes of clock time to complete pre-processing, processing, and post-processing.

3.1.7 FE Model Post-processing

The first criterion evaluated in the post-processing routine is fracture toughness. Mode I and Mode II SERR are calculated for each edge of the delamination boundary and the results are saved in individual files. The following data is sorted in spatial order along the length of each edge and exported to facilitate generating plots if desired: node number, G_I, G_{II}, G_{TOTAL}, and G_{RATIO} (G_{II} / G_{TOTAL}). To calculate SERR, the forces are extracted at the nodes directly at the crack tip. This is done by selecting the elements attached to the node and only above the node. Otherwise, the sum of the forces at the node would equal zero to satisfy equilibrium. These forces are denoted X_{Li}, Y_{Li}, and Z_{Li} in Figure 23. Subsequently, the displacement of the originally coincident nodes is extracted. The upper node has the subscript $L\ell$ while the lower node has the subscript $L\ell^*$ as denoted in Figure 23.

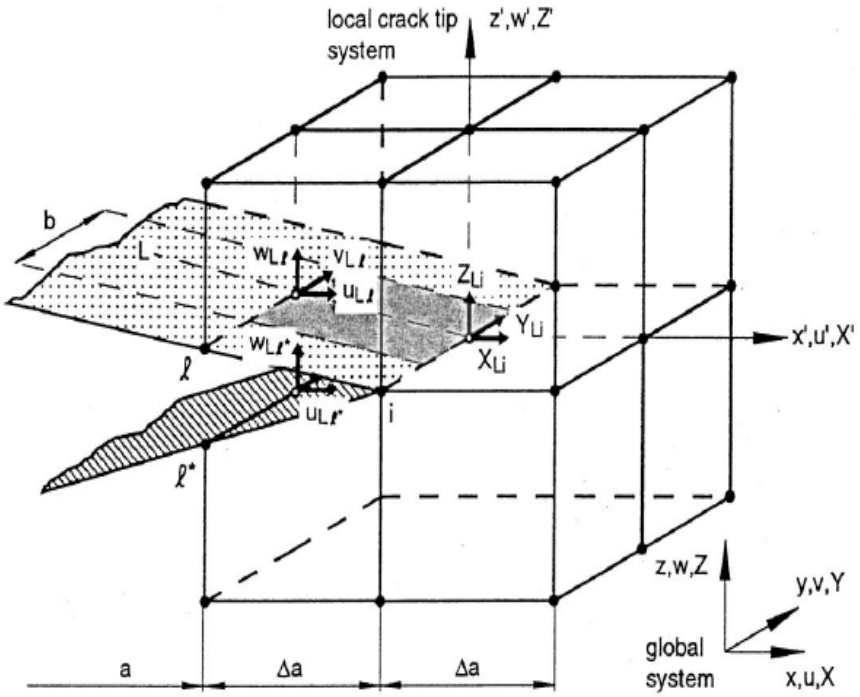


Figure 23: Virtual crack closure technique for eight-noded solid elements[29].

The formulas for calculating Mode I and Mode II SERR are shown in Equations 1 and 2. Δ*A* is the area virtually closed and is defined as the product of Δ*a* and *b*. Alternate forms of these equations are also presented in Krueger and O'Brien for cases where the adjacent elements have varying lengths and/or widths. SERR values are not calculated at the extreme corners of the delamination.

$$G_I = -\frac{1}{2\Delta A} Z_{Li}(w_{L\ell} - w_{L\ell_*}) \quad (1)$$

$$G_{II} = -\frac{1}{2\Delta A} X_{Li}(u_{L\ell} - u_{L\ell_*}) \quad (2)$$

The second criterion evaluated in the post-processing routine is maximum stress failure. Nine failure stress components – tension, compression, and shear in three directions – are entered by the user. Ideally, the code creates an array of maximum strength ratios for each element. This vector is searched for the maximum value and the corresponding element number. Then a table consisting of element number, layer number, direction, and strength ratio is generated. If stress failure has not occurred, the strength ratio can be used to scale the applied load to the predicted failure load. However, the available version of ANSYS (Release 12.1) does not facilitate the automated sorting and filtering of stress failure criteria.

Figure 24 presents SERR distribution along the left edge of a 51 mm (2.0 in.) square delamination in sandwich type 2. The applied load is 50% of the measured ultimate static load for a baseline panel without defects - 13,526 N. The graph on the left is at the skin-core interface while the graph on the right is within the skin. As expected for the given loading condition, the contribution of G_I is essentially zero. The maximum value of G_{II} occurs at mid-span along the left edge of the defect (shear is a maximum at the panel support, Figure 12) and is greater at the skin-core interface (shear is greatest at the neutral axis).

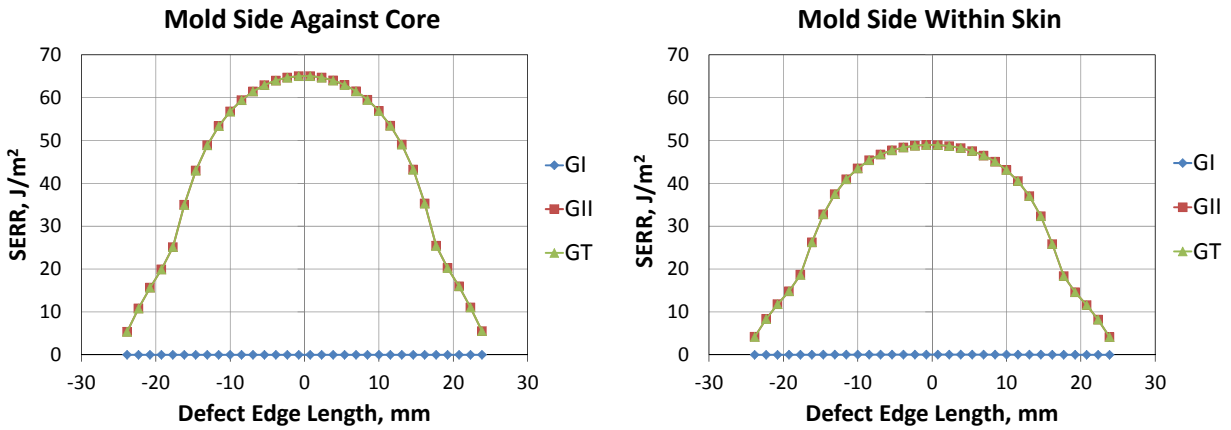


Figure 24: Panel 2 SERR along left edge of 51 mm (2.0 in) delamination – mold side defect.

Figure 25 displays similar data as above for sandwich construction type 4. The applied load is also 50% of the measured ultimate static load for a baseline panel without defects - 3,888 N. The major difference in behavior between the two laminates is that the carbon skins produce a dip in the SERR curve at mid-span along the defect edge. In addition, the peak SERR in the carbon panel is two orders of magnitude lower than the glass panel. This is likely due to the carbon modulus being significantly greater than glass leading to much less displacement.

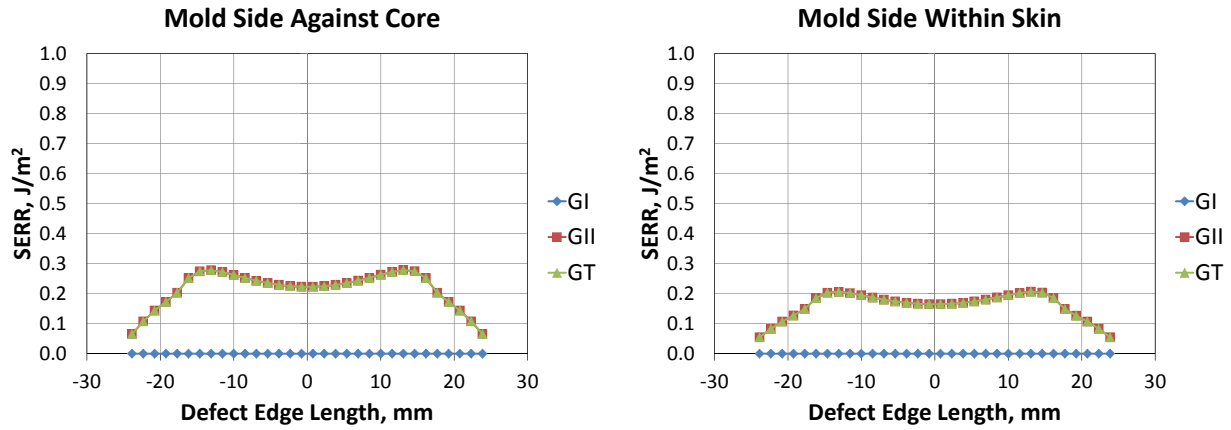


Figure 25: Panel 4 SERR along left edge of 51 mm (2.0 in) delamination – mold side defect.

The curves presented in Figure 26 for sandwich type 2 compare the distribution of Mode II SERR on all sides of the delamination. The graph on the left for a 51 mm (2.0 in.) defect at the skin-core interface shows that the magnitude and relative distribution are similar all around the defect. While the graph on the right for the same size defect within the skin indicates much lower peak Mode II SERR along the front and back edges along with a flatter distribution across the crack front.

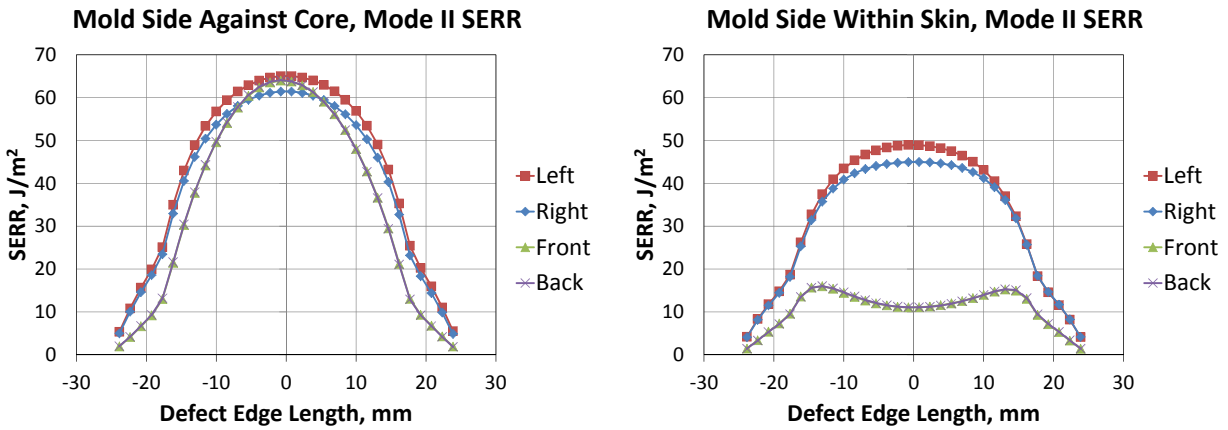


Figure 26: Panel 2 Mode II SERR for 51 mm (2.0 in) delamination – mold side defect.

Similar graphs are presented in Figure 27 for sandwich construction type 4. The SERR values around the defect exhibit the same dip that was observed in the type 2 panel skin defect along the front and back edges. However, this feature is now apparent in both the skin-core and skin defect but along the left and right edges. While very low, the relative magnitudes of the Mode II SERR are closer together around the type 4 skin defect compared to the type 2 skin defect.

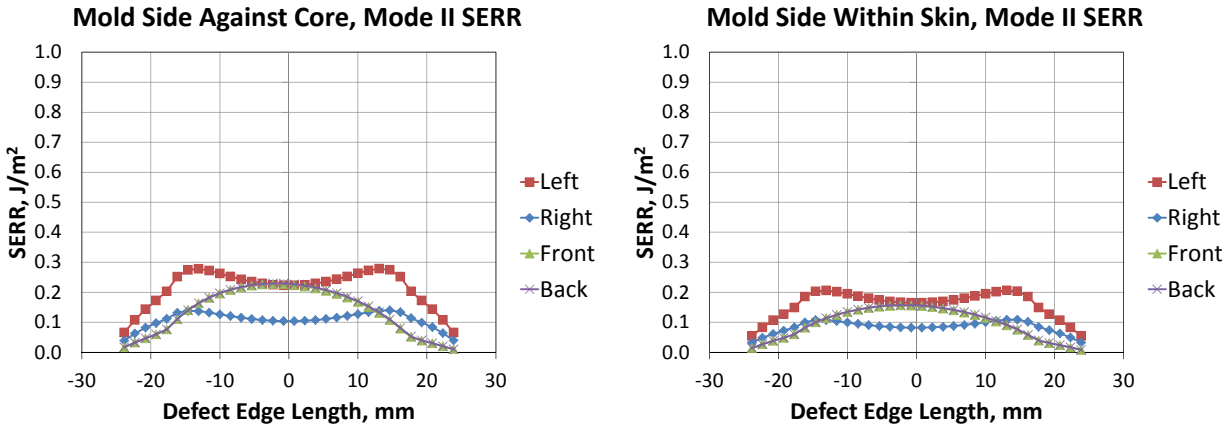


Figure 27: Panel 4 Mode II SERR for 51 mm (2.0 in) delamination – mold side defect.

Figure 28 depicts Mode II SERR along the left edge of a 51 mm (2.0 in.) defect in the type 2 panel (left graph) and the type 4 panel (right graph) at each of the four depth locations. As expected, the type 2 results show the greatest SERR at the skin-core interface. SERR at the skin delamination is slightly higher on the mold (tension) side than the bag side. In contrast, the bag side defects were both lower than the mold side defects for the type 4 carbon panel. This was unexpected given a symmetric laminate.

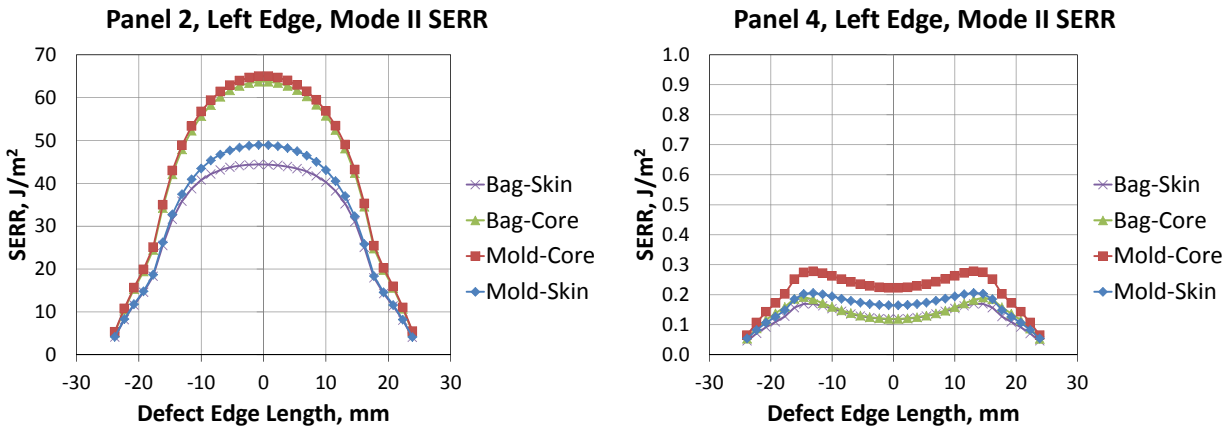


Figure 28: Panels 2 and 4 Mode II SERR for 51 mm (2.0 in) delamination at various depths.

The effect of delamination size on Mode II SERR at the left edge is presented in Figure 29 for type 2 (left side) and type 4 (right side). The type 2 graph shows that doubling the defect size from 25 mm (1.0 in.) to 51 mm (2.0 in.) increases SERR by a factor of 2.2 while moving to a 98 mm (3.875 in.) defect increases SERR by a factor of 4.6. For the type 4 panel, similar relative increases are observed in SERR for the same increase in defect size.

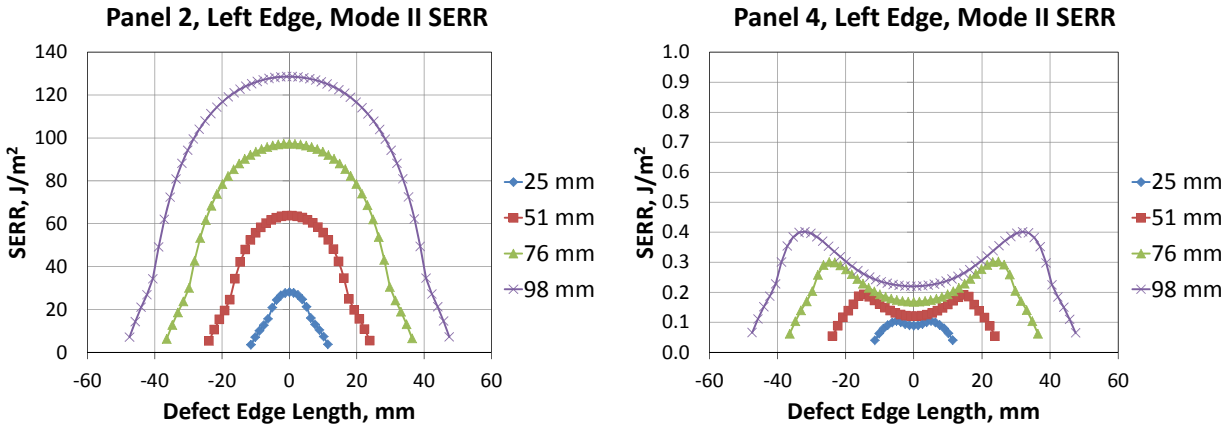


Figure 29: Panels 2 and 4 Mode II SERR for various defect sizes – bag side against core.

Mode II and total SERR are presented in Figure 30 for a 98 mm (3.875 in.) defect at 50% and 100% of the maximum applied static load. In the type 2 panel, doubling the load increased Mode II SERR by a factor of 4 and total SERR by a factor of 3.9. The same ratios for the type 4 panel are 4 and 4.4, respectively. Mixity ratio (G_{II}/G_T) decreases as the delamination size increases.

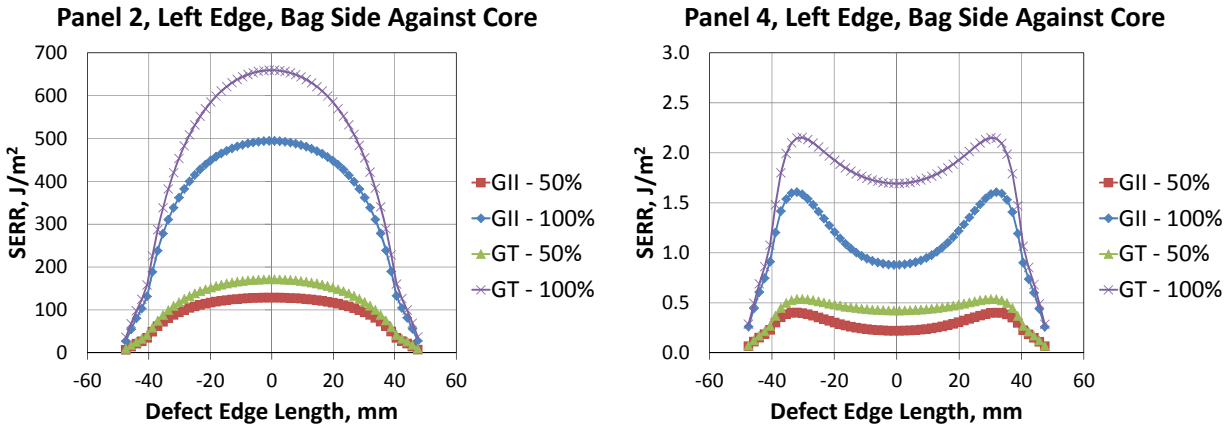


Figure 30: G_{II} and G_T for 98 mm (3.9 in) defect at 50% and 100% load for panels 2 and 4.

Figure 31 presents Mode I and Mode II fracture toughness as a function of flaw size for sandwich types 2 and 4 for a delamination on the bag (compression) side against the core . The plots also include the G_I and G_{II} onset values measured during the material property coupon tests. The only scenario where fracture toughness appears to play a potential role in the performance of the panel is for a 98 mm (3.875 in.) defect at 100% load. In this case, G_I is 165 J/m² (11.3 lb/ft), which is essentially equal to the measured Mode I onset value of 167 J/m² (11.4 lb/ft). Mode I fracture toughness levels in the type 4 panel are still very well below the critical value.

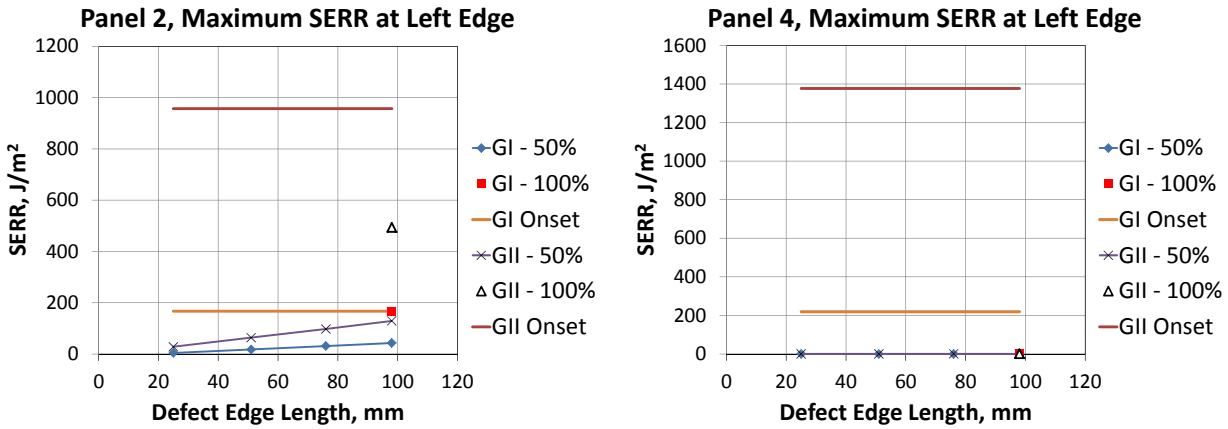


Figure 31: G_I and G_{II} vs. defect size for panels 2 and 4 – bag side against core.

The FE delamination model has proven to be an efficient tool for generating fracture toughness data as a function of delamination size, position, and depth. The APDL input file can easily be manipulated to incorporate different materials and flat panel geometries. The models described above were run on a 64-bit Lenovo ThinkPad with an Intel Core-i7 2.7 GHz CPU. Execution time for the 51 mm (2.0 in.) configurations was approximately five minutes including model generation, solution, and post-processing.

3.2 Strain Rate Effects on Foam Core

3.2.1 Determination of Strain Rates

Evaluation of dynamic loading effects on the mechanical properties of the foam core materials was performed at three shear strain rates. The following strain rates for testing were suggested in the original project proposal:

- Quasi-static strain rate ≈ 0.0008/s
- Intermediate strain rate ≈ 1.25/s
- Slamming strain rate ≈ 2.5/s

For quasi-static loading, both ASTM C273-06 [17] and ASTM C393-06 [20] recommend that the speed of loading be adjusted to produce failure of the specimen within three to six minutes. Standard cross head displacement speeds are also suggested. For C273, the standard suggests a speed of 0.51 mm/min (0.020 in/min), which for the 38.1 mm (1.5 in.) thick specimens used in this study, would produce a shear strain rate of 0.0002/s. In C393, the suggested cross head speed is 6.35 mm/min (0.25 in/min). For the various sandwich constructions and test arrangements used in this study, this cross head speed would produce a shear strain rate ranging from 0.0002/s to 0.0008/s. These values were obtained from analytical predictions, which are described in more detail in Appendix H.

The quasi-static loading rate selected for the C273 tests was 1.83 mm/min (0.072 in/min) for the 38.1 mm (1.5 in.) thick foam core specimens, and 1.52 mm/min (0.06 in/min) for the 31.8 mm (1.25 in.) thick foam core specimens. This results in a strain rate of 0.0008/s for both specimen types.

The strain rate of 0.0008/s was also used for the C393 tests; however , the variation in panel thickness for the five sandwich panel types results in different load head rates for each sandwich panel type. The load head rates used for the C273 and C393 quasi-static strain rate tests are presented in Table 16.

The core shear strain rate chosen as the target slamming rate for this project was 2.0/s. A literature search found little quantitative information regarding core shear strain rates during actual slamming events. Initially, parameters for the C273 and C393 tests were determined based upon a guidance note contained in Det Norske Veritas (DNV) rules for the design of sandwich panels in hulls subjected to slamming loads [30]. DNV specifies that core shear properties should be determined in a bend test performed with a dynamic load such that the core sees a stress rate of 65 MPa/s (9427 psi/s). From predicted test analysis, this stress rate would cause core shear strain rates ranging from 1.3/s to 2.2/s for the different sandwich constructions, using assumed test parameters. It was decided that all tests would be run to the same core shear strain rate target, and 2.0/s was chosen. Also a factor in this decision is that it was felt that the highest actuator speeds needed to obtain the 2.0/s strain rate were within the capabilities of the test equipment intended for use in the study. The load head rates used for the C273 and C393 slamming strain rate tests are presented in Table 16.

The intermediate strain rate target initially chosen was one half of the slamming strain rate, or 1.0/s. Initial C273 tests performed on the H80 foam core material shows that the stress/strain relationships were close for tests performed at 2.0/s and 1.0/s strain rates. Analysis of the data showed that the time it took to fail a specimen at those strain rates was very close. The strain rate effects of foam core material are assumed to be visco-elastic in nature, and therefore are time dependent. There was not enough change in time to failure between tests performed at 2.0/s and 1.0/s to show significantly different stress/strain relationships. It was decided that it would be

better to choose a lower intermediate rate in order to have the test results fall more evenly between the quasi-static and slamming test results. Figure 32 shows the stress-strain results for tests performed on H80 foam core samples at various strain rates. Based on data from this investigation, it was decided to use a strain rate of 0.25/s (1/8 of the slamming rate) for intermediate strain rate testing for both C273 and C393 testing. The load head rates used for the C273 and C393 intermediate strain rate tests are presented in Table 16.

Table 16: Strain and load-head rates used for the C273 and C393 tests.

		Quasi-Static		Intermediate		Slamming	
ASTM Standard	**Foam Core/Panel Type**	***Strain Rate***	***Load Head Rate***	***Strain Rate***	***Load Head Rate***	***Strain Rate***	***Load Head Rate***
		strain/sec	*mm/sec (in/sec)*	*strain/sec*	*mm/sec (in/sec)*	*strain/sec*	*mm/sec (in/sec)*
C273	***H Foam Core***	0.0008	0.0305 (0.00120)	0.25	9.53 (0.375)	2.0	76.2 (3.00)
	M Foam Core		0.0254 (0.00100)		7.95 (0.313)		63.5 (2.50)
C393	***Panel 1***	0.0008	0.106 (0.00417)	0.25	135 (5.32)	2.0	1100 (43.3)
	Panel 2				80.0 (3.15)		637 (25.1)
	Panel 3				110 (4.34)		865 (34.0)
	Panel 4				45.0 (1.77)		371 (14.6)
	Panel 5				77.0 (3.03)		643 (25.3)

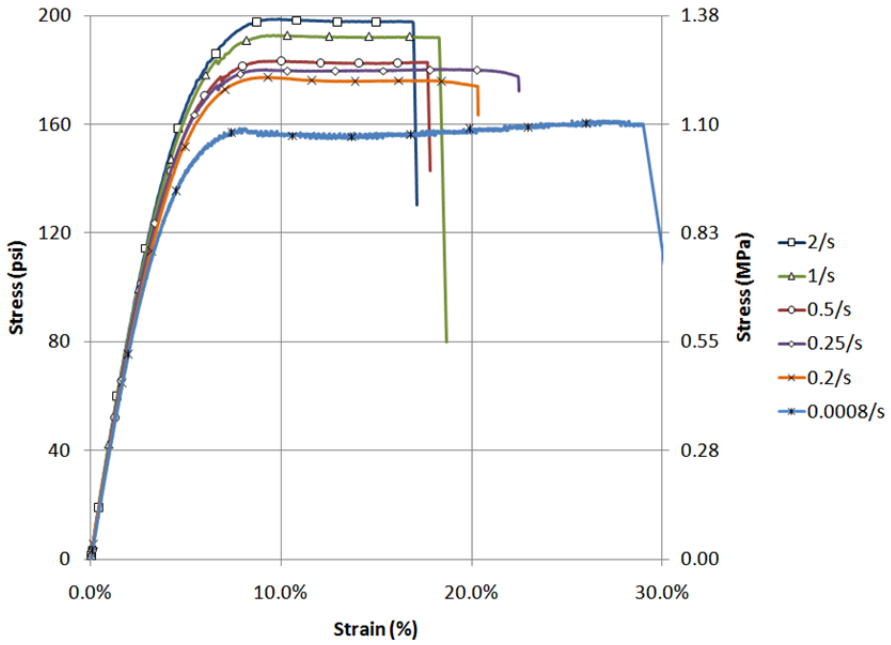


Figure 32: ASTM C273 stress-strain test results for H80 at various strain rates.

3.2.2 ASTM C273 and ASTM C393 Specimen Fabrication

The foam core samples for the C273 foam core shear tests were delivered to AEWC in full sheet form. Overall dimensions of the sheets varied, as previously presented in Table 5

The nominal thickness of the sheets was 38.1 mm (1.5 in.) for the Divinycell H foam cores, and 31.8 mm (1.25 in.) for the Corecell M foam cores. Specimens were sawn from the sheets using a table saw with a carbide tipped blade. The foam core materials are assumed to be isotropic with regard to mechanical properties, therefore orientation of specimens relative to original panel dimensions was not considered to be critical when cutting specimens. The cutting patterns were optimized to obtain the largest number of specimens from each panel. The specimen dimensions were selected to meet the requirements of C273. Table 17 shows the specimen dimension standards used in this project for each foam core type.

Table 17: ASTM C273 foam core specimen dimensions.

Foam Core Type	Core Thickness *mm (in.)*	Specimen Width *mm (in.)*	Specimen Length *mm (in.)*
Corecell M	31.8 (1.25)	51 (2.0)	432 (17.0)
Divinycell H	38.1 (1.50)	51 (2.0)	457 (18.0)

The C273 specimens were assembled by bonding steel plates to the top and bottom of the foam core specimen. The adhesive used to bond the foam to the steel plates was Ashland Pliogrip 7779. Pliogrip 7779 is a two-part urethane adhesive consisting of an isocyanate prepolymer and a polyol curative. The steel plates had overall dimensions of 524 mm × 76.2 mm × 15.9 mm (20.63 in. x 3.00 in. x 0.625 in.). Figure 33 shows the overall dimensions of an assembled specimen for the 38.1 mm (1.50 in.) thick foam cores. The specimens for the 31.8 mm (1.25 in.) foam cores were similar, but used the 432 mm (17.0 in.) foam core length to maintain the desired load line. The geometry of the assembled specimens was designed so that when mounted in the test fixture, the load line passes through diagonally opposite corners of the foam specimen as shown in the schematic in Figure 34. This is a requirement of the C273 standard.

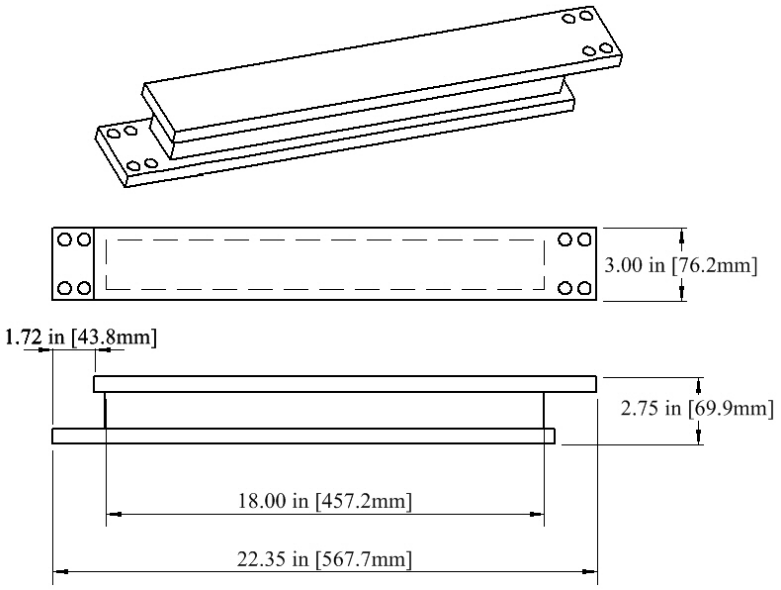


Figure 33: Overall dimensions for the Divinycell H foam core ASTM C273 specimen.

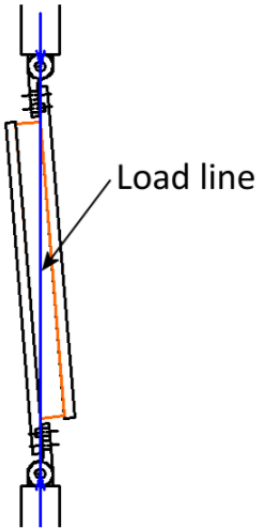


Figure 34: Load line for C273 test.

Labeling and dimensioning of each foam specimen was done before bonding to the steel plates. The thickness and width of each specimen was measured at three points along the length.

An alignment fixture was built to aid the fabrication of the specimens. The fixture was used to hold the steel plates and foam specimens in the proper position relative to each other to insure consistent geometry from specimen to specimen. The bonding surfaces of the steel were prepared by sanding with a 114 mm (4.5 in.), 60-grit, sandpaper flap-wheel on an angle grinder and cleaned with acetone immediately before bonding. The two part Pliogrip 7779 adhesive was mixed by hand and spread evenly across the bonding surfaces of the foam pieces. Once assembled in the alignment fixture, C-clamps were used to clamp all parts together and insure adhesive squeeze-out around all exposed bondline edges (Figure 35). The adhesive squeeze-out was removed. The assembled specimens were placed in an oven at 66°C (150 °F) for 8 hours to insure complete curing of the adhesive before testing.



Figure 35: ASTM C273 specimen being clamped in alignment fixture.

Specimens for the C393 sandwich beam flexure tests were cut from the full size sandwich panels using a water-cooled diamond blade circular saw. The long axis of each specimen was aligned with the zero degree direction of the sandwich panel. Specimen dimensions for each panel type were based upon the guidelines contained in the C393 test standard. Table 18 contains the specimen dimensions for each sandwich construction type and the support spans used for the C393 tests.

Table 18: ASTM C393 specimen dimensions

Sandwich Type	Nominal Thickness *mm (in.)*	Width *mm (in.)*	Length *mm (in.)*	Support span *mm (in.)*	Span-to-Thickness Ratio
1	86.4 (3.4)	178 (7.0)	813 (32.0)	711 (28.0)	8.2
2	45.7 (1.8)	102 (4.0)	559 (22.0)	457 (18.0)	10.0
3	55.9 (2.2)	127 (5.0)	660 (26.0)	559 (22.0)	10.0
4	27.9 (1.1)	76.2 (3.0)	406 (16.0)	305 (12.0)	10.9
5	40.6 (1.6)	102 (4.0)	533 (21.0)	432 (17.0)	10.6

3.2.3 D3039 and D6641 Specimen Fabrication

The D3039 and D6641 tests were conducted to obtain the tension and compression strength and stiffness properties for the core mechanics model. These specimens were cut from the remnants of the sandwich panels from which the C393 test specimens were cut. First, a manageable piece of the panel, of acceptable size for obtaining the specimens, was cut from the larger panel using the wet saw. Then the skins were cut away from the foam core with a band saw, removing as much of the foam core as possible. Any remaining foam core material was scraped away and the skins were then cut to size using the wet saw. The tension specimens were 25.4mm x 254mm (1.0in x 10in) and the compression specimens were 12.7mm x 140mm (0.5in x 5.5in). Testing was conducted as specified in the respective ASTM standards. Results are presented in Appendix F.

3.2.4 Standard Temperature Testing

The C273 foam core shear tests and the C393 sandwich beam flexure tests were conducted at a standard temperature of approximately 21°C (70°F). Descriptions of these tests are provided in the sections that follow.

3.2.4.1 Standard Temperature ASTM C273 Foam Core Shear Testing

Initial trial specimens did not fail in shear, they failed at the bond line, as shown in Figure 36. It was speculated that the type of failure was influenced by the specimen fabrication process; therefore, the process was refined to the method outlined in Section 3.2.2. However, subsequent trial specimens still failed at the bond line. Upon review of the test, it was determined that the selected loading method was causing the premature failures and not the specimen fabrication process. The trial specimens were originally tested with the C273 fixture configured for tension loading. It was determined that this setup created large peeling stresses at the ends of the specimens.

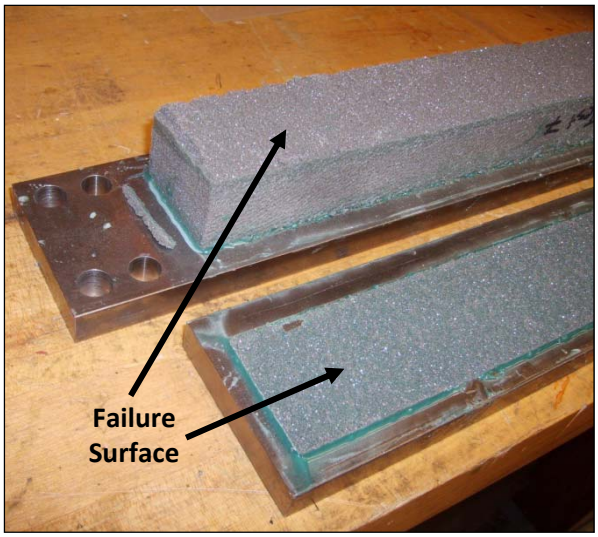


Figure 36: Type of failure observed with the ASTM C273 test in tension.

The C273 test standard also includes an option to conduct the test in compression loading. Since the standard does not recommend one setup over the other, additional trial tests were conducted in compression. This resulted in acceptable failure modes, as indicated by the typical failure presented in Figure 37.



Figure 37: Type of failure observed with ASTM C273 test in compression.

The average ultimate stress obtained from the C273 test performed in tension was at least 10% lower than the average provided by the manufacturer's data sheet. When the C273 test was performed in compression, the average ultimate stress was at most 3% below the average provided by the manufacturer. In addition, the repeatability of the results dramatically improved when the specimens were loaded in compression. The difference between the tension and compression test results is presented in the plot in Figure 38. This graph shows the results of three tests performed in tension and two tests performed in compression. Based on these results, the remaining tests were performed in compression.

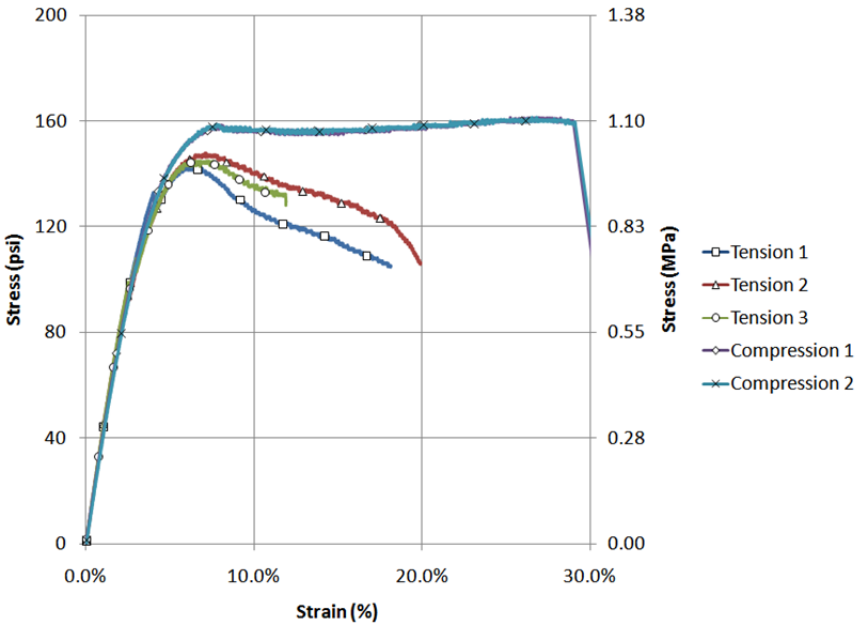


Figure 38: Comparison of tension and compression loading at quasi-static speed.

The C273 standard test method recommends the calculation of three properties: the shear modulus (G), the ultimate shear strength (F_{ult}), and the 2% offset shear stress (F_{off}). The shear modulus is calculated over the strain range of 0.2% to 0.6% strain. Figure 39 shows how the 2% offset shear stress was obtained. The results of the C273 tests conducted at the standard temperature (21°C) are presented in Tables 19-21 for G, F_{ult}, and F_{off}, respectively. The tables also contain the percent change in the results relative to the quasi-static speed test results (ΔQS).

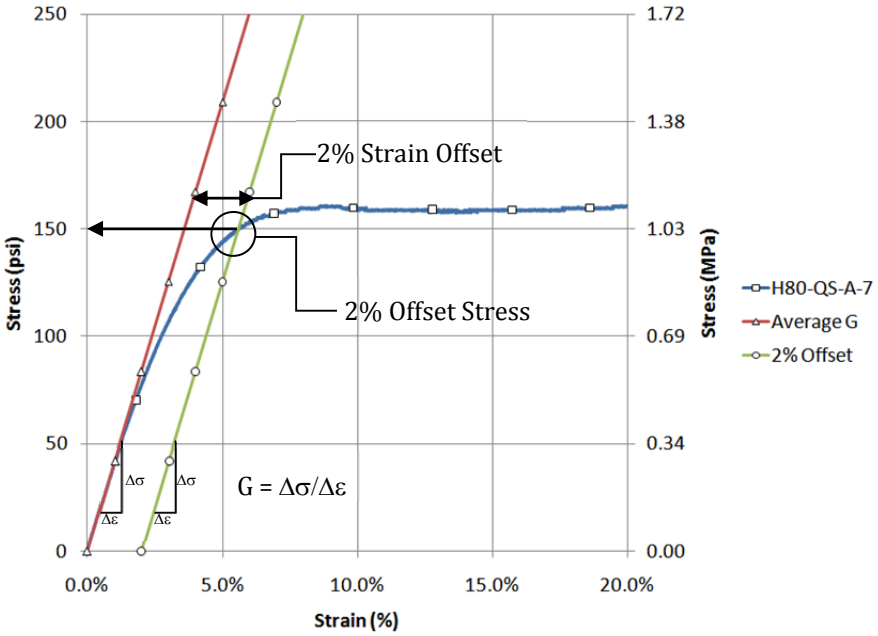


Figure 39: Example of how 2% offset shear stress was calculated.

Table 19: Shear modulus (G) variation due to strain rate at 21°C (70°F).

Foam Core Type		Quasi-Static		Intermediate			Slamming		
		G		G		ΔQS	G		ΔQS
		MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H80	28.83	2.99%	28.84	3.72%	0.0%	31.08	3.31%	7.8%
	H100	37.24	2.81%	39.24	2.54%	5.4%	40.42	6.03%	8.5%
	H130	46.62	0.95%	49.40	1.14%	6.0%	51.63	1.82%	10.8%
Corecell M-Foam Core	M80	32.02	2.45%	32.65	6.96%	2.0%	37.14	6.83%	16.0%
	M100	46.46	2.09%	48.73	4.79%	4.9%	48.32	8.22%	4.0%
	M130	67.16	2.28%	70.12	4.52%	4.4%	77.78	9.11%	15.8%

Table 20: Ultimate strength (F_{ult}) variation due to strain rate at 21°C (70°F).

Foam Core Type		Quasi-Static		Intermediate			Slamming		
		F_{ult}		F_{ult}		ΔQS	F_{ult}		ΔQS
		MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H80	1.121	1.44%	1.265	0.97%	12.9%	1.369	0.77%	22.1%
	H100	1.643	3.01%	1.891	2.11%	15.1%	1.965	2.84%	19.6%
	H130	2.067	2.58%	2.346	0.68%	13.5%	2.497	1.09%	20.8%
Corecell M-Foam Core	M80	1.057	2.82%	1.214	4.30%	14.9%	1.405	1.03%	33.0%
	M100	1.404	1.72%	1.848	0.97%	31.6%	2.008	3.36%	43.0%
	M130	2.147	1.13%	2.723	5.16%	26.9%	3.108	4.16%	44.8%

Table 21: Two percent offset shear strength (F_{off}) variation due to strain rate at 21°C (70°F).

Foam Core Type		Quasi-Static		Intermediate			Slamming		
		F_{off}		F_{off}		ΔQS	F_{off}		ΔQS
		MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H80	1.031	1.71%	1.180	1.09%	14.4%	1.259	0.72%	22.1%
	H100	1.319	3.10%	1.610	1.12%	22.1%	1.673	2.20%	26.9%
	H130	1.674	0.87%	1.996	0.30%	19.2%	2.129	1.81%	27.2%
Corecell M-Foam Core	M80	0.9097	0.96%	1.147	3.94%	26.1%	1.357	1.60%	49.2%
	M100	1.355	1.82%	1.773	2.67%	30.9%	1.929	3.73%	42.4%
	M130	2.066	1.22%	2.632	4.72%	27.4%	2.994	3.22%	44.9%

The stress-strain curves for all the tests performed are presented in Appendix I.

The results presented in Tables 19-21 show that the shear properties of the foam core increase with increasing strain rate. This observation is in line with other research that has been conducted on the relationship between strain rate and tension or compression properties of foam core. As shown in Table 19, the percent change from the quasi-static strain rate (ΔQS) for the shear modulus (G) was at most 6% for the intermediate strain rate and 16% for the slamming strain rate. In comparison, the ΔQS for the shear strength (F_{ult}), shown in Table 20, was at most 32% for the

intermediate strain rate and 45% for the slamming strain rate. This suggests that higher strain rates have a greater effect on the shear strength than the shear stiffness (modulus). Analysis of the test data shows that the 2% offset shear strength (F_{off}) has less variation between samples of the same material tested at the same strain rate than the shear strength (F_{ult}). One reason for this observation could be that for some foam cores the ultimate strength is connected to the shear strain at failure, and the shear strain at failure varied widely between samples in a data set. Also, the H-Core foam had less variation between samples in the same data set than the M-Core foam. This suggests that the H-Core foam has more consistent properties throughout a foam sheet than the M-Core foam does.

The data obtained from a broad sampling of foam core types and strain rates suggests that using strength and stiffness values from quasi-static tests could be too conservative. A more focused study with statistically significant sampling would need to be conducted to generate the scaling factors for shear strength and stiffness properties. If a solid relationship between strain rate and a strength or stiffness property is desired more strain rates need to be examined.

3.2.4.2 Standard Temperature ASTM C393 Sandwich Beam Flexure Testing

One of the most significant challenges to perform the C393 tests at the slamming speeds (Table 16) was the extremely short test duration. As discussed previously, the data was collected at a sampling rate of 5000Hz. The data collected included; time, actuator position, and load. A review of the results indicates that the time from rest (at the start of the test) to the maximum load achieved was less than 0.1 seconds. During this short time span the Instron control system attempted to control the servo valve to accelerate the actuator rod to the desired speed and then maintain that speed without significant overshoot. Obviously, during the acceleration phase the target load head speed was not instantaneously achieved. Also, if there was any overshoot of the target load, it was possible to exceed the target speed. A review of the data does not provide an easily identifiable strain rate. At 5000 sample/sec the data is quite noisy, as seen in Figure 40. Averaging all the data from the start of the test to the end of the test would smooth out the noise, but it would also produce a reduced strain rate, since it includes data from the acceleration phase. In addition averaging all the data from start to finish includes data past the peak load, which could include

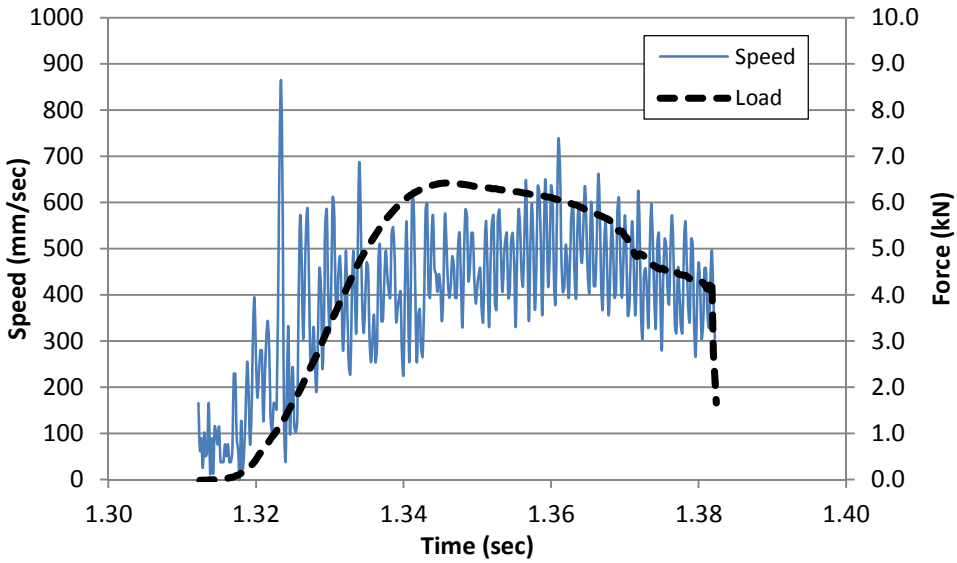


Figure 40: Actuator speed and load versus time for a typical panel (4-S-A-2).

strain rates that exceeded the target rate. Therefore, it was decided that the average strain rate that was achieved just prior to the maximum load would be the most relevant strain rate. A sample of the results for load head speed and the corresponding strain rates for each panel type is presented in Table 22. For this sample of data Panel-Types 1 and 3 did not achieve the target rates while the other three exceeded the target rate at maximum load.

Table 22: Strain and load head rates for the C393 tests at slamming speed.

		Slamming Target		Slamming Actual	
ASTM Standard	Foam Core/Panel Type	*Strain Rate*	*Load Head Rate*	*Strain Rate*	*Load Head Rate*
		strain/sec	*mm/sec (in/sec)*	*strain/sec*	*mm/sec (in/sec)*
C393	***Panel 1***	2.00	1100 (43.3)	1.92	1054 (41.5)
	Panel 2		637 (25.1)	2.51	798 (31.4)
	Panel 3		865 (34.0)	1.63	712 (27.7)
	Panel 4		371 (14.6)	2.24	416 (16.4)
	Panel 5		643 (25.3)	2.34	751 (29.6)

The C393 test standard includes the calculation of three values: the ultimate load (P), the shear stress in the core at failure (τ_{fail}), and the stress in the facing at failure (σ_{face}). The stress in the facing is not necessarily the ultimate stress because the test arrangement was selected to promote shear failure. The results of the C393 tests conducted at the standard temperature (21°C) are presented in Tables 23-25 for P, τ_{fail}, and σ_{face}, respectively. The tables also contain the percent change in the results relative to the quasi-static speed test results (ΔQS).

Table 23: Ultimate load (P) variation due to strain rate at 21°C (70°F).

			Quasi-static		Intermediate			Slamming		
Foam Core Type		Panel Type	P		P		ΔQS	P		ΔQS
			kN	*COV*	*kN*	*COV*		*kN*	*COV*	
Divinycell H Grade Core	H130	1	57.58	6.65%	73.31	2.90%	27.3%	77.97	5.01%	35.4%
	H100	2	15.02	2.60%	18.05	4.20%	20.2%	18.54	5.53%	23.4%
Corecell M-Foam Core	M100	3	19.65	5.02%	25.46	2.25%	29.6%	26.01	1.23%	32.4%
	M80	4	3.994	2.42%	5.289	4.37%	32.4%	5.957	6.78%	49.2%
	M80	5	8.030	2.07%	10.01	0.93%	24.6%	11.18	2.51%	39.3%

Table 24: Core shear stress (τ_{fail}) variation due to strain rate at 21°C (70°F).

			Quasi-static		Intermediate			Slamming		
Foam Core Type		Panel Type	τ_{fail}		τ_{fail}		ΔQS	τ_{fail}		ΔQS
			MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H130	1	1.949	6.20%	2.475	2.66%	27.0%	2.677	8.26%	37.4%
	H100	2	1.741	2.55%	2.095	4.30%	20.4%	2.154	5.43%	23.8%
Corecell M-Foam Core	M100	3	1.445	5.17%	1.857	1.97%	28.5%	1.909	0.56%	32.1%
	M80	4	0.9437	1.65%	1.248	4.40%	32.2%	1.405	6.29%	48.9%
	M80	5	0.9666	2.11%	1.208	0.98%	25.0%	1.354	2.45%	40.1%

Table 25: Facesheet normal stress (σ_{face}) variation due to strain rate at 21°C (70°F).

Foam Core Type		Panel Type	Quasi-static		Intermediate			Slamming		
			σ_{face}		σ_{face}		ΔQS	σ_{face}		ΔQS
			MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H130	1	52.73	7.19%	67.91	2.08%	28.8%	72.44	7.82%	37.4%
	H100	2	48.03	1.90%	58.11	3.93%	21.0%	58.88	6.47%	22.6%
Corecell M-Foam Core	M100	3	65.79	11.0%	84.06	4.63%	27.8%	85.16	3.36%	29.4%
	M80	4	38.94	4.07%	50.20	6.06%	28.9%	54.91	5.20%	41.0%
	M80	5	39.61	5.89%	48.33	6.32%	22.0%	54.93	4.32%	38.7%

It can be seen in Tables 23-25 that the ultimate load, shear stress at failure, and the normal stresses in the facesheets at failure increase with increasing strain rate similar to the trend in the C273 tests. The tables also show that the increase in properties due to strain rate is similar to the increase shown in Tables 19 and 20, suggesting that the increase in performance seen in the material testing is consistent with the sandwich panel testing.

3.2.5 Extreme Temperature Testing

The C273 foam core shear tests and the C393 sandwich beam flexure tests were also conducted at high and low temperature. High temperature was established at 60°C (140°F) and low temperature was -12°C (10°F). The high temperature was selected based on ABS code requiring certain core properties at 60°C (140°F) and data from the literature [31, 32] that showed even white colored fiberglass specimens would exceed 65.6°C (150°F) in an ambient temperature of 35°C (95°F) due to solar radiation. Initially, a low temperature of -18°C (0°F) was selected based on achieving a temperature shift of similar magnitude to the shift between the high and standard temperatures. However, the environmental conditioning equipment and arrangement of the test setup would only reliably produce a test chamber temperature of -12°C (10°F).

Insulated enclosures were constructed around the test fixtures of both the C273 and C393 test stations. A Russells environmental chamber was used to cool or heat the air to reach the target test temperatures. The conditioned air was circulated between the Russells chamber and the test enclosures through 6 in. insulated flexible ducting, which contained inline fans. Specimens were preconditioned to the test temperatures in a separate environmental chamber and moved into the test enclosure just prior to testing. Figure 41 shows the insulated environmental enclosure around the C273 test setup. Figure 42 shows the enclosure for the C393 testing.

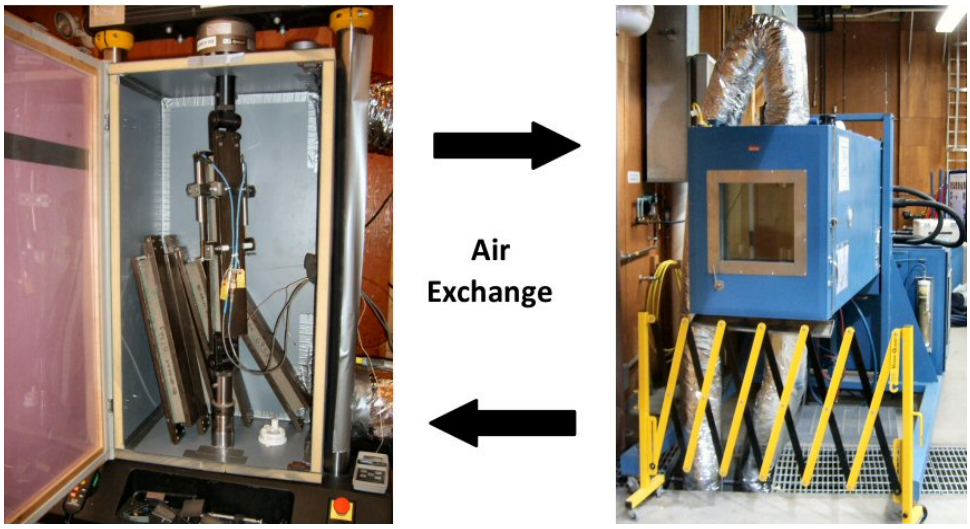


Figure 41: Insulated enclosure for extreme temperature C273 test (left). Russells environmental chamber (right).

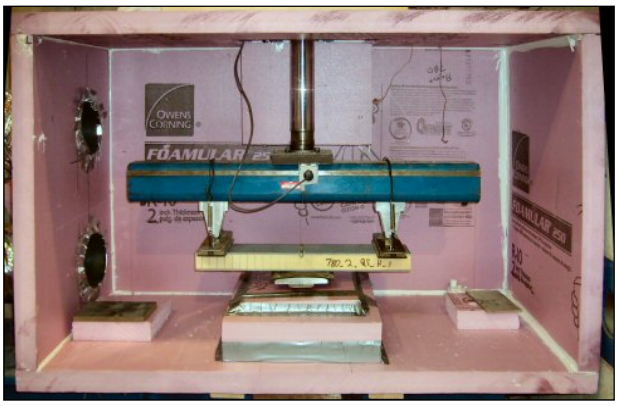


Figure 42: C393 test setup with insulated enclosure with front panel removed.

3.2.5.1 Extreme Temperature ASTM C273 Foam Core Shear Testing

The extreme temperature C273 foam core shear tests were conducted in the compression configuration for the reasons previously discussed in Section 3.2.4.1. The test fixture was enclosed in the temperature-controlled insulated enclosure that was attached to the Russells environmental chamber. The specimens were heated or cooled to the target temperature and held for at least one hour. Then, the specimens were tested in the temperature-controlled environment.

The shear strength and modulus values described in Section 3.2.4.1 were also calculated for the extreme temperature tests. The results of the C273 foam core shear tests conducted at the high temperature (60°C) are presented in Tables 26-28 for G, F_{ult}, and F_{off}, respectively. The results of the C273 foam core shear tests conducted at the low temperature (-12°C) are presented in Tables 29-31 for G, F_{ult}, and F_{off}, respectively. All the tables for both temperature conditions present the percent change in the results relative to the quasi-static speed test results (ΔQS).

Table 26: Shear modulus (G) variation due to strain rate at 60°C (140°F).

Foam Core Type		Quasi-Static		Intermediate			Slamming		
		G		G		ΔQS	G		ΔQS
		MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H80	23.83	1.70%	25.29	0.62%	6.1%	26.67	2.29%	11.9%
	H100	33.19	4.83%	35.89	1.69%	8.2%	35.18	3.28%	6.0%
	H130	40.06	7.17%	42.97	1.20%	7.3%	43.11	2.07%	7.6%
Corecell M-Foam Core	M80	26.28	3.25%	29.29	2.29%	11.5%	30.02	2.87%	12.5%
	M100	35.98	4.13%	40.60	4.36%	12.8%	41.77	3.02%	16.1%
	M130	52.44	2.96%	54.65	4.02%	4.2%	58.64	2.92%	11.8%

Table 27: Ultimate strength (F_{ult}) variation due to strain rate at 60°C (140°F).

Foam Core Type		Quasi-Static		Intermediate			Slamming		
		F_{ult}		F_{ult}		ΔQS	F_{ult}		ΔQS
		MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H80	0.8992	5.50%	1.152	3.10%	28.1%	1.254	1.64%	39.5%
	H100	1.174	5.32%	1.762	3.95%	50.1%	1.842	2.62%	56.9%
	H130	1.477	1.90%	2.203	1.17%	49.1%	2.251	1.20%	52.4%
Corecell M-Foam Core	M80	0.8085	8.97%	1.214	2.82%	50.2%	1.312	2.18%	62.3%
	M100	1.034	5.71%	1.671	2.36%	61.5%	1.762	1.44%	70.4%
	M130	1.539	4.53%	2.250	2.36%	46.2%	2.491	2.34%	61.9%

Table 28: Two percent offset shear strength (F_{off}) variation due to strain rate at 60°C (140°F).

Foam Core Type		Quasi-Static		Intermediate			Slamming		
		F_{off}		F_{off}		ΔQS	F_{off}		ΔQS
		MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H80	0.8084	1.37%	0.9474	2.95%	17.2%	1.053	1.36%	30.2%
	H100	1.077	3.32%	1.343	1.51%	24.7%	1.401	1.71%	30.1%
	H130	1.325	0.93%	1.668	1.22%	25.9%	1.725	0.28%	30.2%
Corecell M-Foam Core	M80	0.7097	3.37%	0.9968	2.30%	40.5%	1.098	0.89%	54.7%
	M100	1.033	5.65%	1.494	1.66%	44.7%	1.611	2.71%	56.0%
	M130	1.536	4.44%	2.085	3.89%	35.8%	2.359	2.68%	53.6%

Table 29: Shear modulus (G) variation due to strain rate at -12°C (10°F).

Foam Core Type		Quasi-Static		Intermediate			Slamming		
		G		G		ΔQS	G		ΔQS
		MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H80	30.06	1.33%	31.12	0.74%	3.5%	33.65	1.42%	11.9%
	H100	41.03	2.12%	41.63	1.63%	1.5%	42.35	1.67%	3.2%
	H130	49.40	1.93%	51.94	1.31%	5.2%	54.11	4.62%	9.6%
Corecell M-Foam Core	M80	36.29	5.40%	35.91	3.11%	-1.1%	36.69	4.90%	1.1%
	M100	46.85	1.76%	51.16	2.52%	9.2%	52.02	1.91%	11.0%
	M130	68.15	1.94%	70.89	2.05%	4.0%	73.71	3.52%	8.2%

Table 30: Ultimate strength (F_{ult}) variation due to strain rate at -12°C (10°F).

Foam Core Type		Quasi-Static		Intermediate			Slamming		
		F_{ult}		F_{ult}		ΔQS	F_{ult}		ΔQS
		MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H80	1.246	1.19%	1.433	1.66%	15.0%	1.537	2.94%	23.4%
	H100	1.796	3.30%	2.090	2.68%	16.4%	2.178	1.84%	21.3%
	H130	2.283	0.97%	2.638	1.01%	15.5%	2.835	1.33%	24.2%
Corecell M-Foam Core	M80	1.218	4.04%	1.469	2.42%	20.6%	1.558	1.04%	27.9%
	M100	1.712	2.23%	2.106	1.36%	23.0%	2.349	1.11%	37.2%
	M130	2.670	2.88%	3.187	2.96%	19.4%	3.331	3.03%	24.8%

Table 31: Two percent offset shear strength (F_{off}) variation due to strain rate at -12°C (10°F).

Foam Core Type		Quasi-Static		Intermediate			Slamming		
		F_{off}		F_{off}		ΔQS	F_{off}		ΔQS
		MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H80	1.168	0.95%	1.318	0.65%	12.8%	1.431	0.77%	22.5%
	H100	1.553	2.63%	1.800	2.67%	15.9%	1.873	1.33%	20.6%
	H130	1.938	1.14%	2.254	1.01%	16.3%	2.413	1.16%	24.5%
Corecell M-Foam Core	M80	1.107	3.49%	1.383	2.69%	25.0%	1.483	0.71%	34.0%
	M100	1.599	2.52%	2.019	1.20%	26.3%	2.263	1.22%	41.5%
	M130	2.468	1.33%	3.024	2.29%	22.6%	3.256	2.88%	32.0%

As discussed in Section 3.2.4.1, the shear modulus (G) and shear strength (F_{ult}) increase with increasing strain rate. Testing at the high temperature (60°C [140°F]), produced results that showed greater increase than testing at the standard temperature (21°C [70°F]), or at the low temperature (-12°C [10°F]) suggesting that temperature may have some effect on the strain rate increases in foam core properties. High temperature quasi-static specimens were susceptible to a form of progressive bond failure after peak load was reached. This bond failure did not affect the intermediate or slamming tests because of the high speed of the test. Similar testing observations to those described in Section 3.2.4.1 were made at high and low temperature. The results of the C273 tests with variation due to temperature are presented in Tables 32-34 for the quasi-static strain rate testing, Tables 35-37 for the intermediate strain rate testing, and Tables 38-40 for the slamming strain rate testing, for G, F_{ult}, and F_{off}, respectively. The tables also present the percent change in the results relative to the Standard Temperature test results (Δ21°C).

Table 32: Shear modulus (G) variation with temperature at quasi-static strain rate.

Foam Core Type		-12°C (10°F)			21°C (70°F)		60°C (140°F)		
		G		Δ21°C	G		G		Δ21°C
		MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H80	30.06	1.33%	4.3%	28.83	2.99%	23.83	1.70%	-17.4%
	H100	41.03	2.12%	10.2%	37.24	2.81%	33.19	4.83%	-10.9%
	H130	49.40	1.93%	6.0%	46.62	0.95%	40.06	7.17%	-14.1%
Corecell M-Foam Core	M80	36.29	5.40%	13.3%	32.02	2.45%	26.28	3.25%	-17.9%
	M100	46.85	1.76%	0.8%	46.46	2.09%	35.98	4.13%	-22.6%
	M130	68.15	1.94%	1.5%	67.16	2.28%	52.44	2.96%	-21.9%

Table 33: Ultimate strength (F_{ult}) variation with temperature at quasi-static strain rate.

Foam Core Type		-12°C (10°F)			21°C (70°F)		60°C (140°F)		
		F_{ult}		Δ21°C	F_{ult}		F_{ult}		Δ21°C
		MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H80	1.246	1.19%	11.2%	1.121	1.44%	0.8992	5.50%	-19.8%
	H100	1.796	3.30%	9.3%	1.643	3.01%	1.174	5.32%	-28.5%
	H130	2.283	0.97%	10.5%	2.067	2.58%	1.477	1.90%	-28.5%
Corecell M-Foam Core	M80	1.218	4.04%	15.2%	1.057	2.82%	0.8085	8.97%	-23.5%
	M100	1.712	2.23%	21.9%	1.404	1.72%	1.034	5.71%	-23.4%
	M130	2.670	2.88%	24.3%	2.147	1.13%	1.539	4.53%	-28.3%

Table 34: Two percent offset shear strength (F_{off}) variation with temperature at quasi-static strain rate.

Foam Core Type		-12°C (10°F)			21°C (70°F)		60°C (140°F)		
		F_{off}		Δ21°C	F_{off}		F_{off}		Δ21°C
		MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H80	1.168	0.95%	13.3%	1.031	1.71%	0.8084	1.37%	-21.5%
	H100	1.553	2.63%	17.8%	1.319	3.10%	1.077	3.32%	-18.4%
	H130	1.938	1.14%	15.7%	1.674	0.87%	1.325	0.93%	-20.9%
Corecell M-Foam Core	M80	1.107	3.49%	21.8%	0.9097	0.96%	0.7097	3.37%	-22.0%
	M100	1.599	2.52%	18.0%	1.355	1.82%	1.033	5.65%	-23.8%
	M130	2.468	1.33%	19.4%	2.066	1.22%	1.536	4.44%	-25.7%

Table 35: Shear modulus (G) variation with temperature at intermediate strain rate.

Foam Core Type		-12°C (10°F)			21°C (70°F)		60°C (140°F)		
		G		Δ21°C	G		G		Δ21°C
		MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H80	31.12	0.74%	7.9%	28.84	3.72%	25.29	0.62%	-12.3%
	H100	41.63	1.63%	6.1%	39.24	2.54%	35.89	1.69%	-8.5%
	H130	51.94	1.31%	5.2%	49.40	1.14%	42.97	1.20%	-13.0%
Corecell M-Foam Core	M80	35.91	3.11%	10.0%	32.65	6.96%	29.29	2.29%	-10.3%
	M100	51.16	2.52%	5.0%	48.73	4.79%	40.60	4.36%	-16.7%
	M130	70.89	2.05%	1.1%	70.12	4.52%	54.65	4.02%	-22.1%

Table 36: Ultimate strength (F_{ult}) variation with temperature at intermediate strain rate.

Foam Core Type		-12°C (10°F)			21°C (70°F)		60°C (140°F)		
		F_{ult}		Δ21°C	F_{ult}		F_{ult}		Δ21°C
		MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H80	1.433	1.66%	13.2%	1.265	0.97%	1.152	3.10%	-8.9%
	H100	2.090	2.68%	10.5%	1.891	2.11%	1.762	3.95%	-6.8%
	H130	2.638	1.01%	12.5%	2.346	0.68%	2.203	1.17%	-6.1%
Corecell M-Foam Core	M80	1.469	2.42%	21.0%	1.214	4.30%	1.214	2.82%	0.0%
	M100	2.106	1.36%	14.0%	1.848	0.97%	1.671	2.36%	-9.6%
	M130	3.187	2.96%	17.0%	2.723	5.16%	2.250	2.36%	-17.4%

Table 37: Two percent offset shear strength (F_{off}) variation with temperature at intermediate strain rate.

Foam Core Type		-12°C (10°F)			21°C (70°F)		60°C (140°F)		
		F_{off}		Δ21°C	F_{off}		F_{off}		Δ21°C
		MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H80	1.318	0.65%	11.7%	1.180	1.09%	0.9474	2.95%	-19.7%
	H100	1.800	2.67%	11.8%	1.610	1.12%	1.343	1.51%	-16.6%
	H130	2.254	1.01%	13.0%	1.996	0.30%	1.668	1.22%	-16.4%
Corecell M-Foam Core	M80	1.383	2.69%	20.6%	1.147	3.94%	0.9968	2.30%	-13.1%
	M100	2.019	1.20%	13.9%	1.773	2.67%	1.494	1.66%	-15.8%
	M130	3.024	2.29%	14.9%	2.632	4.72%	2.085	3.89%	-20.8%

Table 38: Shear modulus (G) variation with temperature at slamming strain rate.

Foam Core Type		-12°C (10°F)			21°C (70°F)		60°C (140°F)		
		G		Δ21°C	G		G		Δ21°C
		MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H80	33.65	1.42%	8.2%	31.08	3.31%	26.67	2.29%	-14.2%
	H100	42.35	1.67%	4.8%	40.42	6.03%	35.18	3.28%	-13.0%
	H130	54.11	4.62%	4.8%	51.63	1.82%	43.11	2.07%	-16.5%
Corecell M-Foam Core	M80	36.69	4.90%	-1.2%	37.14	6.83%	30.02	2.87%	-19.2%
	M100	52.02	1.91%	5.7%	48.32	8.22%	41.77	3.02%	-15.2%
	M130	73.71	3.52%	-5.2%	77.78	9.11%	58.64	2.92%	-24.6%

Table 39: Ultimate strength (F_{ult}) variation with temperature at slamming strain rate.

Foam Core Type		-12°C (10°F)			21°C (70°F)		60°C (140°F)		
		F_{ult}		Δ21°C	F_{ult}		F_{ult}		Δ21°C
		MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H80	1.537	2.94%	12.3%	1.369	0.77%	1.254	1.64%	-8.4%
	H100	2.178	1.84%	10.8%	1.965	2.84%	1.842	2.62%	-6.3%
	H130	2.835	1.33%	13.5%	2.497	1.09%	2.251	1.20%	-9.9%
Corecell M-Foam Core	M80	1.558	1.04%	10.9%	1.405	1.03%	1.312	2.18%	-6.6%
	M100	2.349	1.11%	16.5%	2.008	3.36%	1.762	1.44%	-12.6%
	M130	3.331	3.03%	7.2%	3.108	4.16%	2.491	2.34%	-19.9%

Table 40: Two percent offset shear strength (F_{off}) variation with temperature at slamming strain rate.

Foam Core Type		-12°C (10°F)			21°C (70°F)		60°C (140°F)		
		F_{off}		Δ21°C	F_{off}		F_{off}		Δ21°C
		MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H80	1.431	0.77%	13.7%	1.259	0.72%	1.053	1.36%	-16.4%
	H100	1.873	1.33%	11.9%	1.673	2.20%	1.401	1.71%	-16.3%
	H130	2.413	1.16%	13.3%	2.129	1.81%	1.725	0.28%	-19.0%
Corecell M-Foam Core	M80	1.483	0.71%	9.2%	1.357	1.60%	1.098	0.89%	-19.2%
	M100	2.263	1.22%	17.3%	1.929	3.73%	1.611	2.71%	-16.5%
	M130	3.256	2.88%	8.8%	2.994	3.22%	2.359	2.68%	-21.2%

In general, the results in Tables 32-40 indicate that there are greater changes due to temperature in the strength of the foam core (F_{ult} and F_{off}) than in the stiffness of the foam core (G). These differences are not as pronounced as the differences in the change due to strain rate discussed in Section 3.2.4.1 and earlier in this section. The tables show that generally the increase in a property at low temperature (-12°C [10°F]) is smaller than the decrease in the same property at high temperature (60°C [140°F]). One possible reason for this is that there is a +5.6°C (+10°F) difference in the magnitude of the temperature shift (relative to standard temperature) for the high temperature versus the low temperature. The high temperature tests were conducted 38.9°C (70°F) above the standard temperature, while the low temperature tests were conducted 33.3°C (60°F) below the standard temperature. Another option to explain this could be that the foam core properties have a non-linear temperature response. Another observation from the tables is that higher strain rates do not have a significantly higher change due to temperature than the lower strain rates. This suggests that the change in a property due to temperature is not affected by the strain rate, and therefore the change in a property due to temperature is not a function of strain rate.

While the data qualitatively indicate that the shear strength and stiffness properties have an inverse relation with temperature, a more focused study with statistically significant sampling would need to be conducted to quantify the relation over the operational range of temperatures. Analyzing the data by strain rate shows that the change in a property due to temperature is not a function of strain rate. Based on the limited data from the tests conducted, an extremely simplified model to account for temperature and strain-rate effects on the core shear strength would be:

$$R_u \leq R_o C_t C_r \quad \textbf{(3)}$$

where:

R_u = the required core shear strength

R_o = the characteristic value generated through a B-basis computation of the 2%-offset shear strength from ASTM C273 quasi-static tests performed at standard temperature.

C_t = the temperature correction factor (Table 41)

C_r = the strain rate correction factor (Table 42)

Table 41: Temperature correction factor (C_t).

Temperature	Core Material	C_t
-12°C (10°F)	PVC	1.10 - 1.15
	SAN	1.05 - 1.20
21°C (70°F)	PVC	1.0
	SAN	1.0
60°C (140°F)	PVC	0.75 – 0.80
	SAN	0.75 – 0.85

Table 42: Strain-rate correction factor (C_r).

Strain Rate	Core Material	C_r
Quasi-Static *(0.0008/s)*	PVC	1.0
	SAN	1.0
Intermediate *(0.25/s)*	PVC	1.10 - 1.25
	SAN	1.20 – 1.45
Slamming *(2.0/s)*	PVC	1.2 – 1.3
	SAN	1.30 – 1.55

Factors for strain rates and temperatures not explicitly listed in Tables 41 and 42 should be compiled from test data and NOT interpolated between the stated factors. If a more accurate relationship between temperature and a strength or stiffness property is desired, testing at more temperatures needs to be examined, but would not require testing at multiple strain rates due to their independence.

3.2.5.2 Extreme Temperature ASTM C393 Sandwich Beam Flexure Testing

The extreme temperature C393 sandwich beam flexure tests were conducted in a manner similar to the standard temperature tests. The test fixture was enclosed in the temperature-controlled box that was attached to the Russell environmental chamber described above. The specimens were heated or cooled to the target temperature and held for at least one hour. Then, the specimens were tested in the temperature-controlled environment.

The ultimate load, core shear stress, and skin stress values described in Section 3.2.4.2 were also calculated for the extreme temperature tests. These results are presented in Tables 43-45 for the high temperature tests, and in Tables 46-48 for the low temperature tests. The tables also present the percent change in the results relative to the quasi-static test results (ΔQS).

Table 43: Ultimate load (*P*) variation due to strain rate at 60°C (140°F).

			Quasi-static		Intermediate			Slamming		
Foam Core Type		Panel Type	P		P		ΔQS	P		ΔQS
			kN	*COV*	*kN*	*COV*		*kN*	*COV*	
Divinycell H Grade Core	H130	1	46.96	3.82%	58.47	4.34%	24.5%	61.93	8.69%	31.9%
	H100	2	12.04	6.61%	14.64	1.78%	21.6%	15.85	1.54%	31.6%
Corecell M-Foam Core	M100	3	14.27	2.59%	21.01	3.28%	47.3%	22.66	2.45%	58.8%
	M80	4	3.266	4.01%	4.439	2.39%	35.8%	5.008	2.52%	53.2%
	M80	5	5.651	1.89%	8.336	2.82%	47.5%	9.673	3.36%	71.2%

Table 44: Core shear stress (τ_{fail}) variation due to strain rate at 60°C (140°F).

Foam Core Type		Panel Type	Quasi-static		Intermediate			Slamming		
			τ_{fail}		τ_{fail}		ΔQS	τ_{fail}		ΔQS
			MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H130	1	1.584	3.55%	1.975	4.06%	24.7%	2.109	7.91%	33.1%
	H100	2	1.395	6.60%	1.697	1.52%	21.6%	1.845	1.88%	32.2%
Corecell M-Foam Core	M100	3	1.041	2.11%	1.543	3.38%	48.2%	1.659	2.49%	59.4%
	M80	4	0.7703	3.59%	1.052	2.80%	36.4%	1.182	3.10%	53.2%
	M80	5	0.6824	1.76%	1.006	2.86%	47.4%	1.164	2.76%	70.6%

Table 45: Facesheet normal stress (σ_{face}) variation due to strain rate at 60°C (140°F).

Foam Core Type		Panel Type	Quasi-static		Intermediate			Slamming		
			σ_{face}		σ_{face}		ΔQS	σ_{face}		ΔQS
			MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H130	1	42.89	3.30%	54.20	3.84%	26.4%	57.18	8.96%	33.3%
	H100	2	38.26	7.86%	46.86	1.53%	22.5%	50.83	2.63%	32.9%
Corecell M-Foam Core	M100	3	45.46	4.25%	68.52	3.20%	50.7%	74.28	5.25%	63.4%
	M80	4	31.50	5.11%	41.57	5.12%	32.0%	46.22	4.22%	46.7%
	M80	5	27.26	2.75%	40.63	4.55%	49.1%	47.81	3.07%	75.4%

Table 46: Ultimate load (P) variation due to strain rate at -12°C (10°F).

Foam Core Type		Panel Type	Quasi-static		Intermediate			Slamming		
			P		P		ΔQS	P		ΔQS
			kN	*COV*	*kN*	*COV*		*kN*	*COV*	
Divinycell H Grade Core	H130	1	67.42	4.84%	82.77	4.16%	22.8%	82.92	6.79%	23.0%
	H100	2	16.79	4.26%	19.85	5.53%	18.3%	20.38	3.34%	21.4%
Corecell M-Foam Core	M100	3	22.60	1.57%	28.61	1.84%	26.6%	29.16	7.93%	29.0%
	M80	4	4.903	1.16%	5.940	4.02%	23.8%	6.026	2.71%	22.9%
	M80	5	9.339	3.00%	11.56	1.38%	23.8%	12.27	3.50%	31.4%

Table 47: Core shear stress (τ_{fail}) variation due to strain rate at -12°C (10°F).

Foam Core Type		Panel Type	Quasi-static		Intermediate			Slamming		
			τ_{fail}		τ_{fail}		ΔQS	τ_{fail}		ΔQS
			MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H130	1	2.272	4.54%	2.879	3.33%	26.7%	2.833	7.22%	24.7%
	H100	2	1.947	4.14%	2.306	5.48%	18.4%	2.369	3.22%	21.7%
Corecell M-Foam Core	M100	3	1.657	1.44%	2.093	1.75%	26.3%	2.115	7.13%	27.6%
	M80	4	1.159	1.13%	1.406	3.90%	23.9%	1.482	3.04%	27.9%
	M80	5	1.125	2.43%	1.391	1.56%	23.6%	1.472	3.39%	30.8%

Table 48: Facesheet normal stress (σ_{face}) variation due to strain rate at -12°C (10°F).

Foam Core Type		Panel Type	Quasi-static		Intermediate			Slamming		
			σ_{face}		σ_{face}		ΔQS	σ_{face}		ΔQS
			MPa	*COV*	*MPa*	*COV*		*MPa*	*COV*	
Divinycell H Grade Core	H130	1	60.90	4.84%	78.44	4.67%	28.8%	77.59	7.28%	27.4%
	H100	2	53.78	5.47%	63.21	5.48%	17.5%	65.12	4.20%	21.1%
Corecell M-Foam Core	M100	3	74.40	4.09%	93.84	4.05%	26.1%	96.22	6.33%	29.3%
	M80	4	46.84	2.21%	56.44	6.68%	20.5%	58.09	4.92%	24.0%
	M80	5	46.59	2.41%	57.11	2.86%	22.6%	59.37	3.51%	27.4%

As discussed in Section 3.2.5.1 the data in the tables above show the same increases as their C273 counterparts. The increases due to strain rate displayed by the foam core material seem to be transferring to the sandwich panel, including the trend where the high temperature strain rate increases are greater than the standard and low temperature strain rate increases.

The results of the ASTM C393 tests with variation due to temperature are presented in Tables 49-51 for the quasi-static strain rate testing, Tables 52-54 for the intermediate strain rate testing, and Tables 55-57 for the slamming strain rate testing, for P, τ_{fail}, and σ_{face}, respectively. The tables also present the percent change in the results relative to the standard temperature test results (Δ21°C).

Table 49: Ultimate load (P) variation with temperature at quasi-static strain rate.

Foam Core Type		Panel Type	-12°C (10°F)			21°C (70°F)		60°C (140°F)		
			P		Δ21°C	P		P		Δ21°C
			kN	*COV*		*kN*	*COV*	*kN*	*COV*	
Divinycell H Grade Core	H130	1	67.42	4.84%	17.1%	57.58	6.65%	46.96	3.82%	-18.5%
	H100	2	16.79	4.26%	11.7%	15.02	2.60%	12.04	6.61%	-19.8%
Corecell M-Foam Core	M100	3	22.60	1.57%	15.0%	19.65	5.02%	14.27	2.59%	-27.4%
	M80	4	4.903	1.16%	22.8%	3.994	2.42%	3.266	4.01%	-18.2%
	M80	5	9.339	3.00%	16.3%	8.030	2.07%	5.651	1.89%	-29.6%

Table 50: Core shear stress (τ_{fail}) variation with temperature at quasi-static strain rate.

Foam Core Type		Panel Type	-12°C (10°F)			21°C (70°F)		60°C (140°F)		
			τ_{fail}		Δ21°C	τ_{fail}		τ_{fail}		Δ21°C
			MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H130	1	2.272	4.54%	16.6%	1.949	6.20%	1.584	3.55%	-18.7%
	H100	2	1.947	4.14%	11.9%	1.741	2.55%	1.395	6.60%	-19.8%
Corecell M-Foam Core	M100	3	1.657	1.44%	14.7%	1.445	5.17%	1.041	2.11%	-28.0%
	M80	4	1.159	1.13%	22.8%	0.9437	1.65%	0.7703	3.59%	-18.3%
	M80	5	1.125	2.43%	16.4%	0.9666	2.11%	0.6824	1.76%	-29.4%

Table 51: Facesheet normal stress (σ_{face}) variation with temperature at quasi-static strain rate.

Foam Core Type		Panel Type	-12°C (10°F)			21°C (70°F)		60°C (140°F)		
			σ_{face}		Δ21°C	σ_{face}		σ_{face}		Δ21°C
			MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H130	1	60.90	4.84%	15.5%	52.73	7.19%	42.89	3.30%	-18.7%
	H100	2	53.78	5.47%	12.0%	48.03	1.90%	38.26	7.86%	-20.3%
Corecell M-Foam Core	M100	3	74.40	4.09%	13.1%	65.79	11.0%	45.46	4.25%	-30.9%
	M80	4	46.84	2.21%	20.3%	38.94	4.07%	31.50	5.11%	-19.1%
	M80	5	46.59	2.41%	17.6%	39.61	5.89%	27.26	2.75%	-31.2%

Table 52: Ultimate load (P) variation with temperature at intermediate strain rate.

Foam Core Type		Panel Type	-12°C (10°F)			21°C (70°F)		60°C (140°F)		
			P		Δ21°C	P		P		Δ21°C
			kN	*COV*		*kN*	*COV*	*kN*	*COV*	
Divinycell H Grade Core	H130	1	82.77	4.16%	12.9%	73.31	2.90%	58.47	4.34%	-20.2%
	H100	2	19.85	5.53%	10.0%	18.05	4.20%	14.64	1.78%	-18.9%
Corecell M-Foam Core	M100	3	28.61	1.84%	12.4%	25.46	2.25%	21.01	3.28%	-17.5%
	M80	4	5.940	4.02%	14.7%	5.289	4.37%	4.439	2.39%	-16.1%
	M80	5	11.56	1.38%	15.5%	10.01	0.93%	8.336	2.82%	-16.7%

Table 53: Core shear stress (τ_{fail}) variation with temperature at intermediate strain rate.

Foam Core Type		Panel Type	-12°C (10°F)			21°C (70°F)		60°C (140°F)		
			τ_{fail}		Δ21°C	τ_{fail}		τ_{fail}		Δ21°C
			MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H130	1	2.879	3.33%	16.3%	2.475	2.66%	1.975	4.06%	-20.2%
	H100	2	2.306	5.48%	10.1%	2.095	4.30%	1.697	1.52%	-19.0%
Corecell M-Foam Core	M100	3	2.093	1.75%	12.7%	1.857	1.97%	1.543	3.38%	-16.9%
	M80	4	1.406	3.90%	15.0%	1.248	4.40%	1.052	2.80%	-15.7%
	M80	5	1.391	1.56%	15.2%	1.208	0.98%	1.006	2.86%	-16.7%

Table 54: Facesheet normal stress (σ_{face}) variation with temperature at intermediate strain rate.

Foam Core Type		Panel Type	-12°C (10°F)			21°C (70°F)		60°C (140°F)		
			σ_{face}		Δ21°C	σ_{face}		σ_{face}		Δ21°C
			MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H130	1	78.44	4.67%	15.5%	67.91	2.08%	54.20	3.84%	-20.2%
	H100	2	63.21	5.48%	8.8%	58.11	3.93%	46.86	1.53%	-19.4%
Corecell M-Foam Core	M100	3	93.84	4.05%	11.6%	84.06	4.63%	68.52	3.20%	-18.5%
	M80	4	56.44	6.68%	15.0%	50.20	6.06%	41.57	5.12%	-17.2%
	M80	5	57.11	2.86%	18.2%	48.33	6.32%	40.63	4.55%	-15.9%

Table 55: Ultimate load (*P*) variation with temperature at slamming strain rate.

Foam Core Type		Panel Type	-12°C (10°F)			21°C (70°F)		60°C (140°F)		
			P		Δ21°C	P		P		Δ21°C
			kN	*COV*		*kN*	*COV*	*kN*	*COV*	
Divinycell H Grade Core	H130	1	82.92	6.79%	6.3%	77.97	5.01%	61.93	8.69%	-20.6%
	H100	2	20.38	3.34%	9.9%	18.54	5.53%	15.85	1.54%	-14.5%
Corecell M-Foam Core	M100	3	29.16	7.93%	12.1%	26.01	1.23%	22.66	2.45%	-12.9%
	M80	4	6.026	2.71%	1.2%	5.957	6.78%	5.008	2.52%	-15.9%
	M80	5	12.27	3.50%	9.7%	11.18	2.51%	9.673	3.36%	-13.5%

Table 56: Core shear stress (τ_{fail}) variation due to temperature at slamming strain rate.

Foam Core Type		Panel Type	-12°C (10°F)			21°C (70°F)		60°C (140°F)		
			τ_{fail}		Δ21°C	τ_{fail}		τ_{fail}		Δ21°C
			MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H130	1	2.833	7.22%	5.8%	2.677	8.26%	2.109	7.91%	-21.2%
	H100	2	2.369	3.22%	10.0%	2.154	5.43%	1.845	1.88%	-14.3%
Corecell M-Foam Core	M100	3	2.115	7.13%	10.8%	1.909	0.56%	1.659	2.49%	-13.1%
	M80	4	1.482	3.04%	5.5%	1.405	6.29%	1.182	3.10%	-15.9%
	M80	5	1.472	3.39%	8.7%	1.354	2.45%	1.164	2.76%	-14.0%

Table 57: Facesheet normal stress (σ_{face}) variation with temperature at slamming strain rate.

Foam Core Type		Panel Type	-12°C (10°F)			21°C (70°F)		60°C (140°F)		
			σ_{face}		Δ21°C	σ_{face}		σ_{face}		Δ21°C
			MPa	*COV*		*MPa*	*COV*	*MPa*	*COV*	
Divinycell H Grade Core	H130	1	77.59	7.28%	7.1%	72.44	7.82%	57.18	8.96%	-21.1%
	H100	2	65.12	4.20%	10.6%	58.88	6.47%	50.83	2.63%	-13.7%
Corecell M-Foam Core	M100	3	96.22	6.33%	13.0%	85.16	3.36%	74.28	5.25%	-12.8%
	M80	4	58.09	4.92%	5.8%	54.91	5.20%	46.22	4.22%	-15.8%
	M80	5	59.37	3.51%	8.1%	54.93	4.32%	47.81	3.07%	-13.0%

The C393 results in Tables 49-57 mirror the C273 results in Tables 32-40 presented in Section 3.2.5.1.

3.2.6 Foam Core Mechanics Models

The Mechanics Model for the foam core is an extension of a moment-curvature analysis. The model is split into five modules. The modular approach permits easy development and customization of the overall analysis depending on boundary conditions, single skin or sandwich construction, and other relevant factors. The five modules are a set of MATLAB functions that are called from a controlling function. (The MATLAB code for these functions can be found in Appendix J.) In general, the designer must supply the function with:

- the length (*L*) of the beam in inches,
- the width (*b*) of the beam in inches,
- the thickness of the skins and core in inches,
- the elastic moduli of the skins and core in psi,
- the curve fit parameters, and
- the failure stress and strain criteria for the skins and core.

The code is set up to take multiple rows of inputs, where each row will be treated as a different run of the code.

The model makes a number of assumptions that must be understood and accounted for to properly use the model. The assumptions are:

- The elastic moduli of the core and facesheets are linear with strain and do not change with strain rate.
- The core material does not compress through the thickness.
- The model uses sandwich beam assumptions in the calculation of the bending and shear rigidities.
- The thickness of the core is much greater than the thickness of the skins *(The skins are not accounted for in the calculation of the shear rigidity).*
- The elastic modulus of the core is much less than the elastic moduli of the skins *(The core is not accounted for in the calculation of the bending rigidity).*

The first module is the moment-curvature analysis. This module must be supplied with the normal strain at the top extreme fiber, the elastic modulus of each of the layers, and the thickness of each of the layers. This module calculates the distance to the neutral axis and then the nominal moment capacity. The stress and strain diagrams are presented in Figure 43. Refer to Figure 43 for the variables that are used in the equations that follow.

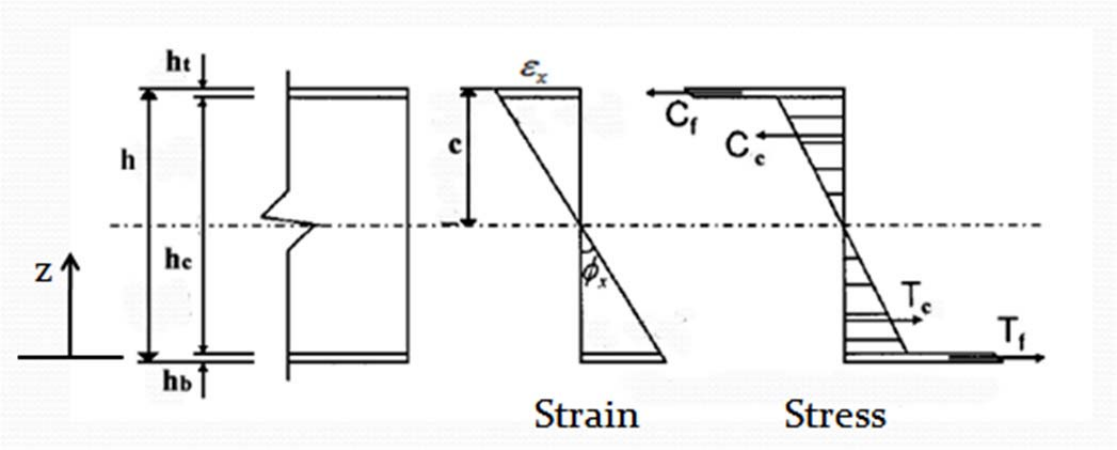


Figure 43: Stress and strain diagrams for the moment-curvature analysis.

Equation 4 presents strain as a function of depth:

$$\varepsilon(z) = \frac{\varepsilon_x}{c}(z - h + c) \quad \textbf{(4)}$$

where:

ε_x = the selected normal strain at the extreme top fiber,

z = the distance from the bottom of the sandwich laminate,

h = the total height of the sandwich laminate, and

c = the distance from the extreme top fiber to the neutral axis.

The nominal moment capacity is the sum of T_f, T_c, C_f, and C_c about the neutral axis.

$$T_f + T_c + C_f + C_c = 0 \quad \textbf{(5)}$$

where:

T_f = the tension in the bottom skin,

T_c = the tension in the core,

C_f = the compression in the top skin, and

C_c = the compression in the core.

The final forms of T_f, T_c, C_f and C_c are presented in Equations 6-9:

$$T_f = E_b \frac{\varepsilon_x}{c}\left(\tfrac{1}{2}h_b - h + c\right)h_b b \quad \textbf{(6)}$$

$$T_c = bE_c\left(\frac{\varepsilon_x}{c}\left(\frac{-c}{2} + ch - \frac{h_b^2}{2} + hh_b - ch_b\right)\right) \quad \textbf{(7)}$$

$$C_f = E_t \frac{\varepsilon_x}{c}\left(c - \tfrac{1}{2}h_t\right)h_t b \quad \textbf{(8)}$$

$$C_c = bE_c\left(\frac{\varepsilon_x}{2c}(h_t - c)^2\right) \quad \textbf{(9)}$$

where:

E_b = the elastic modulus of the bottom skin,

h_b = the thickness of the bottom skin,

b = the width of the section,

E_c = the elastic modulus of the core,

E_t = the elastic modulus of the top skin, and

h_t = the thickness of the top skin.

To find the location of the neutral axis, substitute Equations 6-9 into Equation 5 and solve for *c*.

The second module takes the moment calculated in the first module and calculates the load and shear produced by that moment. This module depends on the loading configuration and boundary conditions, so it must be updated when the loading configuration or boundary conditions change.

The third module takes the shear force calculated in the second module and calculates the shear stress. Then the module calculates the shear strain from the curve fit of the core consitutive relationship. Finally, the module calculates the shear modulus at the point defined by the shear stress and strain. This module requires the shear force from the second module, the width of the section, the thickness of the core, and the curve fit parameters.

The shear stress is calculated with Equation 10:

$$\tau = \frac{V}{b\left(\frac{h_t}{2} + h_c + \frac{h_b}{2}\right)} \quad \textbf{(10)}$$

where:

τ = the shear stress,

V = the shear force,

b = the width of the section,

h_b = the thickness of the bottom skin,

h_c = the thickness of the core, and

h_t = the thickness of the top skin.

The shear strain is calculated with Equation 11:

$$\gamma = \frac{\tau_{max}}{G}\tanh^{-1}\left(\frac{\tau}{\tau_{max}}\right) \quad \textbf{(11)}$$

where:

γ = the shear strain,

τ_{max} = a curve fit parameter signifying the asymptote of the hyperbolic tangent function, and

G = a curve fit parameter signifying the slope of the hyperbolic tangent function at the origin

The shear modulus is calculated using the centered difference formula, Equation 12. This formula estimates the slope of the line tangent to the point of interest with the slope of a line going through one point $\Delta\gamma$ on each side of the point of interest. This estimate gets more accurate as $\Delta\gamma$ goes to zero.

$$G = \frac{\left(\tau_{\gamma+\Delta\gamma} - \tau_{\gamma-\Delta\gamma}\right)}{\left(\left(\gamma+\Delta\gamma\right)-\left(\gamma-\Delta\gamma\right)\right)} \quad \textbf{(12)}$$

The fourth module takes the shear modulus calculated in the third module and calculates the deflection of the beam. This calculation depends on the load and boundary conditions being represented. The shear modulus changes on every iteration of the code so the calculation of the incremental deflection is essential to calculating the total deflection. First the new shear rigidity must be calculated. Shear rigidity is the measure of the resistance of the beam to shear deformation. Next, the incremental change in load must be calculated to calculate the incremental deflection. The incremental deflection is calculated using First Order Shear Deformation theory and Equation 13, which states that the total deflection, $\Delta\delta$, is the sum of the incremental deflections due to bending, $\Delta\delta_B$, and shear, $\Delta\delta_S$.

$$\Delta\delta = \Delta\delta_B + \Delta\delta_S = \frac{\Delta P L^3}{48EI} + \frac{\Delta P L}{4kAG} \quad \textbf{(13)}$$

where:

ΔP = the change in load,

L = the length of the beam,

EI = the bending rigidity, and

kAG = the shear rigidity.

The fifth module is the failure analysis. The average stress in the top and bottom skins (computed in the first module) are compared with the maximum allowable stress for each of the skins. If one of the skins exceeds the maximum allowable stress, the model stops computing. The average shear stress in the core material (computed in the third module) is compared to the ultimate shear stress of the material. If the actual shear stress exceeds the ultimate, the code stops computing. The code in the fifth module also compares the strain in the top skin, bottom skin and core to the respective ultimate strains.

As it is, the model has a number of limitations; additional work could be done on the model to mitigate some of these limitations. First, the model requires effective strength and stiffness properties for the skins. These effective properties take into account the entire skin laminate, not the individual plies. This limitation makes it cumbersome to see what happens when one layer in a skin laminate is changed. The model could be expanded to include a module that calculates the effective properties based on Classical Lamination Theory before the moment-curvature analysis. Second, the model currently requires the parameters for the curve fit to be supplied. This means that a designer using the model must look up those parameters in a separate table or graph. The model could be expanded to let the designer choose the material, density, strain rate, and temperature and have the model get the curve fit parameters. The third limitation is that this model is calibrated for beams and most shipboard applications would be modeled as plates. Further study would be needed to extend this model to plates.

The results of the model were conservative at each of the strain rates and temperatures for all of the sandwich panel types, except for Panel 5. This means that the model results under-predicted the load deflection curve when compared to the experimental data. Two of these curves are presented in Figures 44 and 45; the rest can be found in Appendix J. The Model's high and low

bounds shown in the figures were constructed using the 95th percentile of the model inputs, which were created from the variation in the test results for the respective experimental data set. These bounds do not include measurement uncertainty.

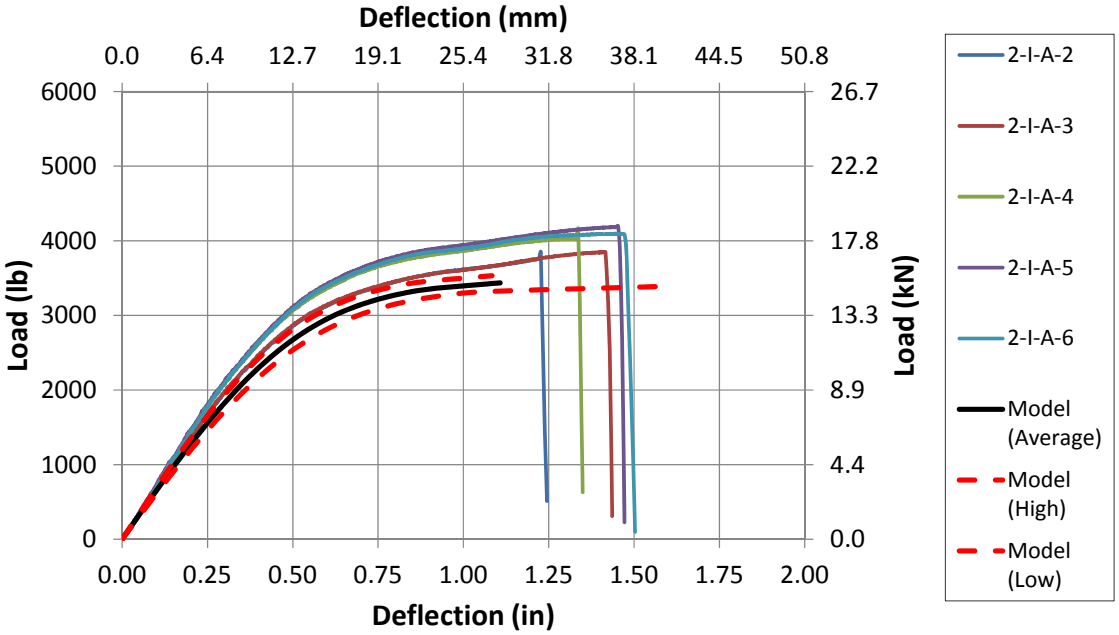


Figure 44: Model and experimental results for panel 2 at intermediate rate and standard temperature.

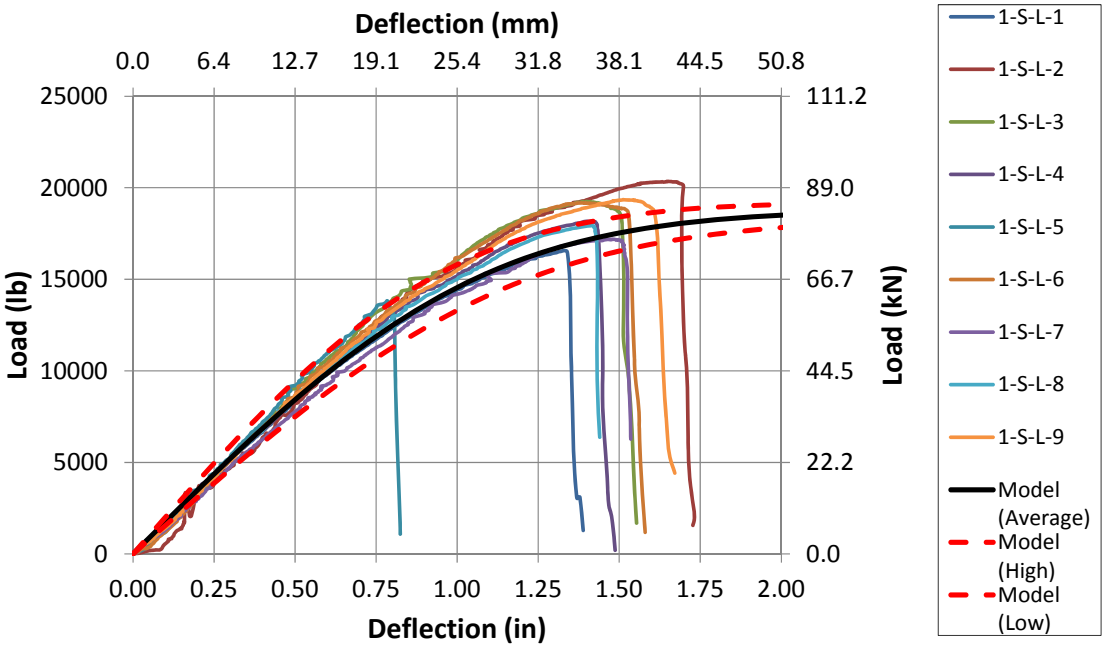


Figure 45: Model and experimental results for panel 1 at slamming rate and low temperature

The model always over-predicted the load deflection curve for Panel 5. Panel 5 was also the only panel that always failed in skin buckling. The compression-side facesheet was so thin that it could not be tested in compression; therefore, the model was run using an estimate. It is believed that the thin compression skin was affecting the load deflection response and that is why the model over predicted the results. A typical curve for sandwich panel type 5 is presented in Figure 46. The rest of the curves can be found in Appendix J.

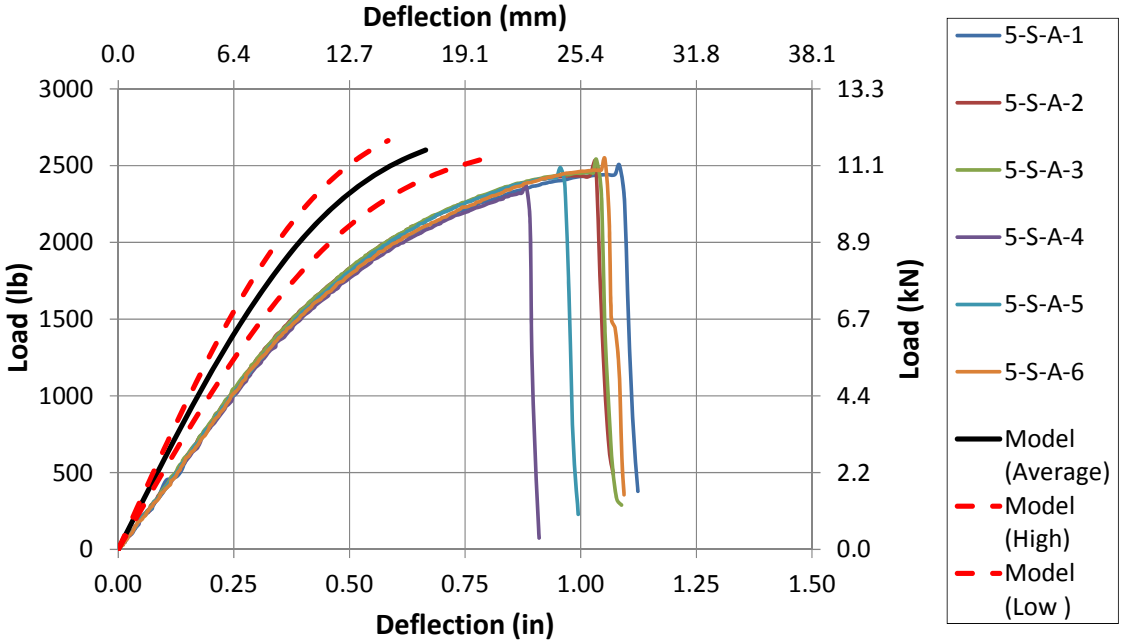


Figure 46: Model and experimental results for panel 5 at slamming rate and standard temperature.

3.3 Impact Resistant Laminates

3.3.1 Impact Test Panel Fabrication

The 11 sandwich panel configurations presented in Figure 1 were fabricated at HSB facilities. A ProSet epoxy resin system (LV117/237) was used for the fabrication. The details of the construction of each panel are outlined in the quality assurance sheets in Appendix A.

A total of 380 coupon samples were tested with the 15.9 mm (0.625 in.) diameter tup. After conversations with the ONR Steering Committee regarding similar testing, an additional 285 specimens were produced and tested with a 51 mm (2.0 in.) diameter tup.

3.3.2 Impact Testing Results

Calculations for the energy delivered to the panel during the impact event are based on the formula:

$$E = \frac{1}{2}mv^2 \quad \textbf{(14)}$$

The time required for the carriage to travel 25.4mm (1.0 in.) was used to calculate the carriage velocity, which was then used in the energy formula. The measured timing event was triggered to occur within 0.25 inches of the impactor striking the top surface of the specimen.

Each panel was visually inspected after impact for signs of cracking and splitting on each surface and along the edges of the panel, especially at the skin/core interface. The damage was found to be in the form of either linear cracking or circular blistering. The panel was then marked on the bottom to indicate the extent of the damage found with either a straight line to indicate a linear crack (Figure 47), or crossed arrows and a circle to identify circular blistering (Figure 48). Failed panels were assigned a designation of 1 in HDC electronic form 10.03.1. Failure is defined when both skins and the core were visibly breached by the impactor such that moisture could pass through the sample in line with the path of travel of the impactor. By sorting failures by panel core type it was possible to determine which core type displayed the least amount of failures and the energy required for the failure. The results were then analyzed by type of specimen and energy level to verify that each group had at least 80% of tested samples reach the failure threshold criteria.

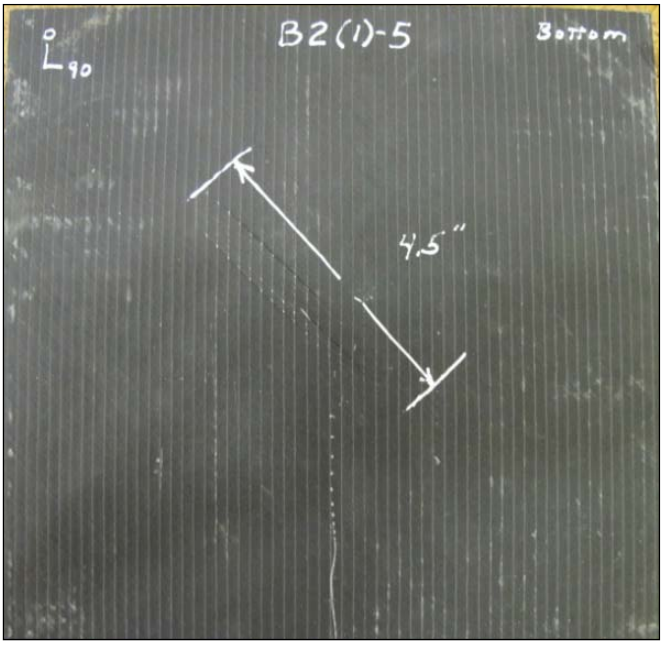


Figure 47: Typical linear failure as indicated on the bottom of the specimen.

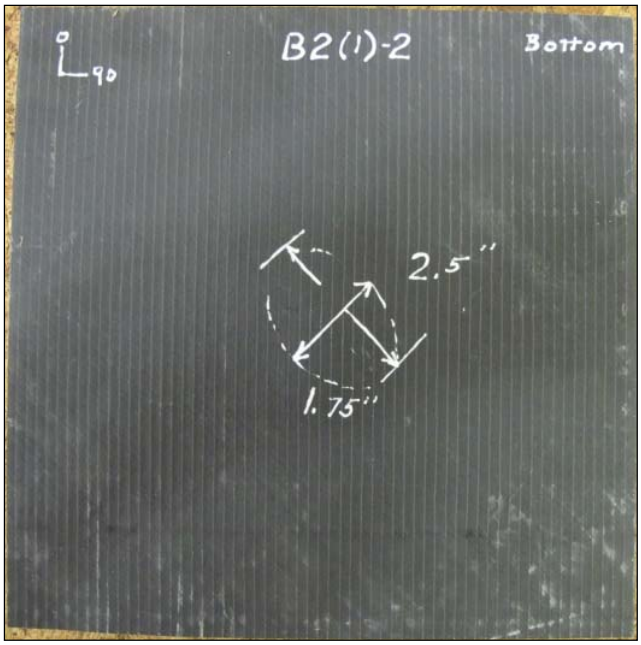


Figure 48: Example of two-directional failure (blistering) on the bottom of the specimen.

A digital photo was taken of each test specimen after the tup had impacted the sample. Selected specimens were bisected and each half was photographed in order to document internal damage. Examples of bisected specimens are presented in Figures 49 and 50 for the 15.9 mm (0.625 in.) and 51 mm (2.0 in.) tups, respectively.

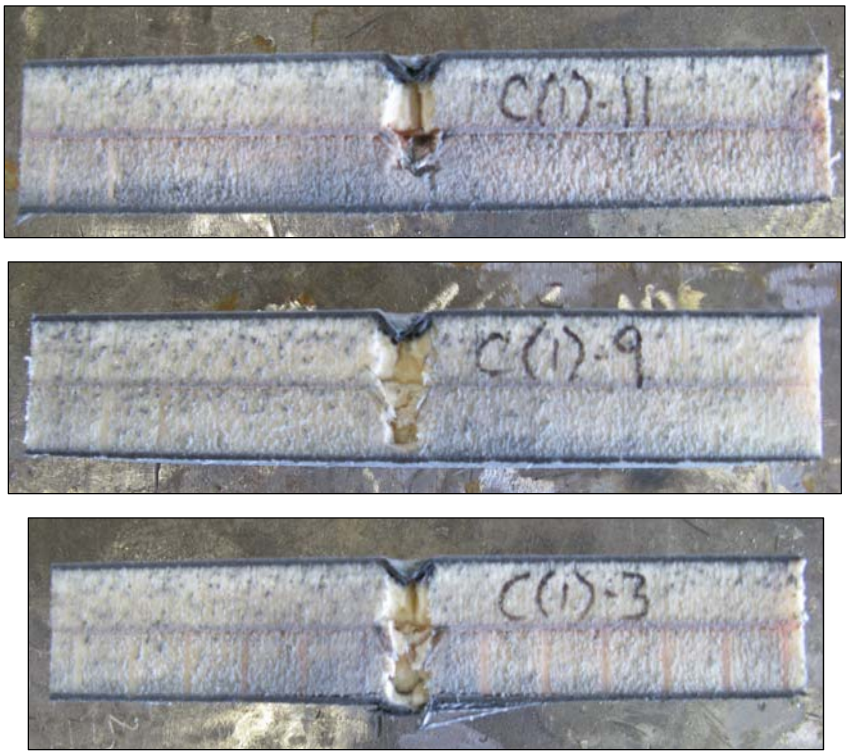


Figure 49: Bisected samples showing internal damage from the 15.9 mm (0.625 in.) tup.

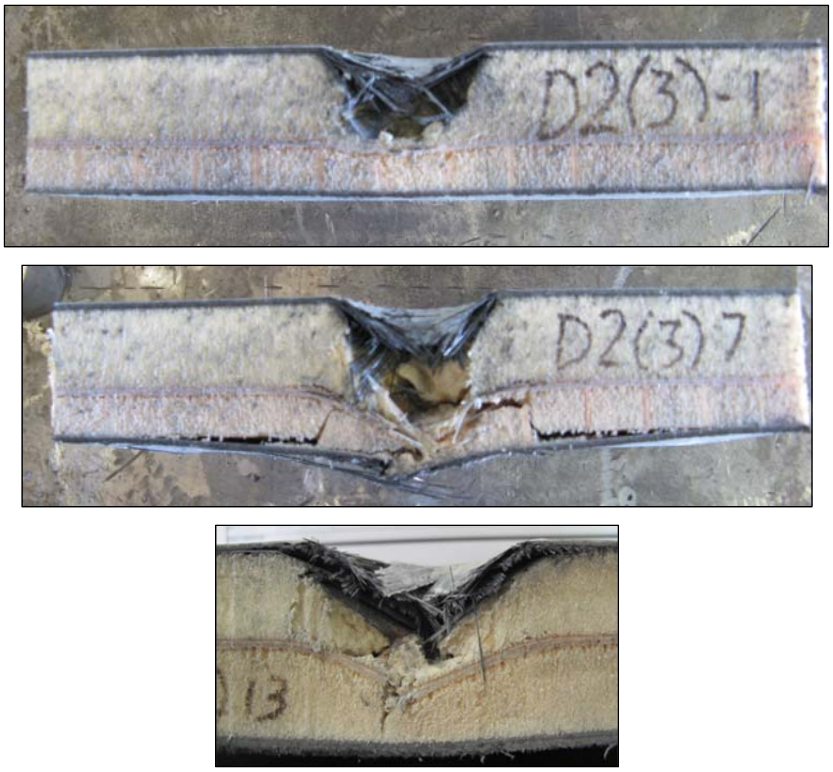


Figure 50: Bisected samples showing internal damage from the 51 mm (2.0 in.) tup.

The results of the 15.9 mm (0.625 in.) tup impact tests are presented in Table 58. The table includes the drop height, carriage weight, average failure energy, specimen quantities, and specimen failure count for each of the 11 core types tested. The individual test energy levels ranged from 83 to 198 J (61 to 147 ft-lb), at velocities from 3.9 to 5.4 m/sec (13 to 18 ft/sec) when testing with the 15.9 mm (0.625 in.) tup. Of the 380 specimens that were tested with the 15.9 mm (0.625 in.) diameter tup, 73 specimens met the criteria of failure. The mean value for the penetration depth of the tup into the panels that achieved the failure criteria was 45.2 mm (1.78 in.) with a COV of 8.8%. The nominal panel thickness was 43 mm (1.7 in.). The range of impact energies for these failures was 147.8-198.6 J (109-146.5 ft-lb), with a mean of 174.4 J (128.6 ft-lb) and a COV of 6.0%. Of these specimens, samples from configuration 'A' (interleaving layer at core/skin interface) had fewer failures and the highest failure threshold.

Table 58: Impact test results for the 15.9 mm (0.625 in.) tup.

Panel Type	Drop Height	Carriage Weight	Average Failure Energy	Specimen Quantity	Specimen Failures	
	m (ft)	*kg (lb)*	*J (ft-lb)*	*#*	*#*	*%*
A	1.68 (5.5)	11.91 (26.27)	180.3 (133.0)	15	3	20
B	1.68 (5.5)	11.91 (26.27)	180.2 (132.9)	5	2	40
B	1.52 (5.0)	11.91 (26.27)	168.3 (124.2)	5	4	80
B2	1.68 (5.5)	11.91 (26.27)	181.7 (134.0)	5	5	100
B2	1.52 (5.0)	11.91 (26.27)	166.9 (123.1)	5	2	40
B3	1.68 (5.5)	11.91 (26.27)	181.8 (134.1)	5	1	20
B3	1.37 (4.5)	11.91 (26.27)	153.8 (113.5)	5	1	20
C	1.68 (5.5)	11.91 (26.27)	181.7 (134.0)	5	4	80
C	1.52 (5.0)	11.91 (26.27)	166.9 (123.1)	5	3	60
C	1.37 (4.5)	11.91 (26.27)	147.9 (109.1)	5	1	20
C2	1.68 (5.5)	11.91 (26.27)	183.4 (135.3)	5	5	100
C2	1.52 (5.0)	11.91 (26.27)	165.6 (122.1)	5	3	60
C3	1.68 (5.5)	11.91 (26.27)	181.7 (134.0)	5	4	80
C3	1.52 (5.0)	11.91 (26.27)	166.9 (123.1)	5	1	20
D	1.68 (5.5)	11.91 (26.27)	181.7 (134.0)	5	4	80
D	1.52 (5.0)	11.91 (26.27)	165.6 (122.1)	5	5	100
D	1.37 (4.5)	11.91 (26.27)	147.9 (109.0)	5	4	80
D2	1.68 (5.5)	11.91 (26.27)	181.7 (134.0)	5	5	100
D2	1.52 (5.0)	11.91 (26.27)	165.6 (122.1)	5	4	80
D3	1.68 (5.5)	11.91 (26.27)	185.1 (136.5)	5	5	100
D3	1.52 (5.0)	11.91 (26.27)	166.9 (123.1)	5	1	20
D4	1.68 (5.5)	11.91 (26.27)	181.7 (134.0)	5	5	100
D4	1.52 (5.0)	11.91 (26.27)	168.3 (124.2)	5	2	40

The results of the 51 mm (2.0 in.) tup impact tests are presented in Table 59. The table includes the drop height, carriage weight, average failure energy, specimen quantities, and specimen failure count for each of the 11 core types tested. The individual energy levels imparted to the panels by the 51 mm (2.0 in.) diameter tup ranged from 406 to 1361 J (299 to 1002 ft-lb), at velocities from 6.7 to 7.6 m/s (22 to 25 ft/sec). Of the 285 specimens that were tested with the 51 mm (2.0 in.) diameter tup, 47 specimens met the failure criteria. The mean value for the penetration depth of the tup into the panels that achieved failure criteria was 53 mm (2.1 in.) with a COV of 7.1%. The nominal panel thickness was 43 mm (1.7 in.). The range of impact energies for these failures was 981-1084 J (724-800 ft-lb), with a mean value of 1046 J (771.5 ft-lb). Of these specimens, samples from configuration 'B' (equal density cores with interleave layer 1/3 into the core) had fewer failures and the highest failure thresholds.

Table 59: Impact test results for the 51 mm (2.0 in.) tup.

Panel Type	Drop Height	Carriage Weight	Average Failure Energy	Specimen Quantity	Specimen Failures	
	m (ft)	*kg (lb)*	*J (ft-lb)*	*#*	*#*	*%*
A	1.01 (7.0)	56.7 (125)	1084 (797)	5	5	100
A	1.83 (6.0)	56.7 (125)	989 (728)	5	5	100
A	1.83 (6.0)	56.7 (125)	918 (675)	5	3	60
B	3.05 (10)	34.0 (75.0)	1032 (760)	10	3	30
B	2.13 (7.0)	56.7 (125)	1112 (818)	1	1	100
B	2.13 (7.0)	56.7 (125)	1118 (822)	1	1	100
B	2.13 (7.0)	56.7 (125)	1066 (784)	7	5	71
B2	3.05 (10)	34.0 (75.0)	872 (642)	10	0	0
B3	3.05 (10)	34.0 (75.0)	997 (733)	5	0	0
C	3.05 (10)	34.0 (75.0)	998 (734)	5	1	20
C	2.13 (7.0)	56.7 (125)	1039 (764)	5	4	80
C	1.83 (6.0)	56.7 (125)	993 (731)	5	3	60
C2	3.05 (10)	34.0 (75.0)	999 (735)	5	0	0
C3	2.29 (7.5)	56.7 (125)	1280 (942)	3	2	67
C3	2.13 (7.0)	56.7 (125)	1169 (860)	3	1	33
C3	1.98 (6.5)	56.7 (125)	1057 (778)	5	2	40
D	3.05 (10)	34.0 (75.0)	1014 (746)	5	4	80
D2	3.05 (10)	34.0 (75.0)	996 (733)	5	3	60
D3	3.05 (10)	34.0 (75.0)	1004 (739)	5	1	20
D4	3.05 (10)	34.0 (75.0)	981 (721)	5	4	80

Calculated results of each group of test specimens are annotated on HDC electronic form 10.03.1 and are made available for inspection.

For both the 15.9 mm (0.625 in.) and the 51 mm (2.0 in.) diameter test series, when failure occurred, the foam core compacted in line with the tip of the tup and was then forced through the underlying laminate material by the tup.

Specimens tested with the 51 mm (2.0 in.) tup showed significantly more propagation of damage than the specimens tested with the 15.9 mm (0.625 in.) diameter tup. The smaller diameter tup produced localized damage to the foam core and interleaving while the larger diameter tup caused widespread damage radiating away from the point of impact. Future testing should be performed on specimens that have an overall unsupported dimension 10 times the impactor diameter to reduce the edge effects

4 Conclusions and Recommendations

4.1 Summary of Findings

Numerous lessons have been learned and valuable observations have been recorded as a result of the investigations conducted in this study. The highlights from each of the research investigations are presented below.

4.1.1 Nondestructive Testing Evaluation

- Shearography was successful at locating all of the delaminations in the panels and proved to be the fastest method to locate the defects. It clearly outlines the extent of the defect, but does not provide information as to the depth of the defect within the laminate.
- The UT evaluation was successful at locating all of the delaminations in the panels. It provides a rough outline of the defect and clearly indicates the depth of the delamination within the laminate, but it can be a time consuming task to scan large areas. UT evaluation is best if used in conjunction with a method that locates problem areas quickly, like shearography.
- The SIDER analysis failed at identifying delaminations in the foam cored sandwich panels. The noise levels in the signals, which caused the problems, are thought to be a result of the simply supported boundary conditions. SIDER has had success in the past, but with fixed boundary conditions like those found in a subcomponent of a larger structure.
- Thermography failed to identify the delaminations in the sandwich panels.
- The fatigue testing of the large sandwich panels did not produce any failures and was not successful at propagating the delaminations within the panel. The possible reasons were investigated and are addressed in the addendum report (Appendix E).
- The FE delamination model developed with APDL proved to be an efficient tool for generating strain energy release rate data as a function of delamination size, position, and depth within the foam cored sandwich panels. The APDL input files can be easily manipulated by an investigator to incorporate different materials and flat panel geometries.
- The FE model confirmed that the peak SERR generated during the fatigue testing of the large panels was not sufficient to propagate the delaminations embedded within the panels.

4.1.2 Strain Rate Effects on Foam Core

- Shear material properties of foam cored sandwich panels obtained through quasi-static testing may be considered too conservative when designing for dynamic events such as slamming. Shear modulus and shear strength increased by as much as 16% and 45%, respectively, over the same properties generated with quasi-static loading at standard temperature.
- The shear material properties of the foam core carried over into the sandwich beam flexure tests where the core shear stress increased by as much as 49% over the quasi-static test results.

- The shear strength and stiffness properties of the foam core exhibited an inverse relation with temperature. A more focused study that includes more temperature variations would be required to determine the exact relationship over the operational range of temperatures.
- Shear material properties of the foam cored sandwich panels tested at temperatures above and below the standard environment resulted in increased properties when tested at higher strain rates. However, while the relative increase of the shear modulus remained constant across all temperatures, the relative increase in shear strength increased with increasing temperature, while maintaining a similar COV in the results.
- The properties generated during the sandwich beam flexure tests conducted at high and low temperature exhibited an increase with increasing strain rate and an inverse relation with temperature. The relative increase in properties at a given strain rate increased with increasing temperature.
- A mechanics model based on a moment-curvature analysis was generated to model the foam cored laminates. The model uses the physical dimensions of the specimen and the material properties and failure criteria of the constituent materials to generate plots and results.
- The core mechanics model could be improved with further development to overcome the current limitations and extend it to an analysis of plate structures.

4.1.3 Impact Testing of Sandwich Laminates

- For both tup sizes, it is reasonable to compare the number of failures of groups A, B, C, and D panels at the same or very similar energy levels.
- For both tup sizes, it is reasonable to compare the number of failures of the baseline B panel with the B2 and B3 panel results at the same or very similar energy levels. The same is true for C to C2 and C3, as well as D to D2 and D3 results.
- It is probably not reasonable to make other comparisons.
- With the 15.9mm (0.625 in) diameter tup, the group A panel results were better than the group B, C, and D results.
- With the 15.9mm (0.625 in) diameter tup, there is no obvious trend shown when using higher density foam cores.
- With the 50.8mm (2 in) diameter tup, the B panel results were better than the A, C, and D panel results.
- With the 50.8mm (2 in) diameter tup, it appears that higher density foam cores improve the results.
- Energies required to produce failure with the 51 mm (2.0 in.) tup were approximately six times greater than those required with the 15.9 mm (.0625 in.) tup.
- Future testing should utilize panels with the total planar supported dimension that is at least 10 times the diameter of the tup to avoid edge effects.

4.2 Recommendations

As a result of the investigations undertaken in this project, the following recommendations for methodology and future work are being proposed.

4.2.1 Nondestructive Testing Evaluation

- A combination of NDT techniques would be the best approach for ship structures. Combined techniques might include a large scale investigation (like SIDER) to identify possible trouble spots, followed by a detailed investigation (Shearography and/or UT) to determine the extent of the defects.
- Further investigations with UT sensors should include phased array technology. This technology allows scanning of larger areas in less time by incorporating roller-probes and automated scanning. Phased arrays utilize encoders to produce C-scans to show a detailed outline of the defect and also provide the depth of the defect.
- Recommendations to address the issues encountered during the fatigue testing of the large sandwich panels with defects are provided in the addendum report (Appendix E).

4.2.2 Strain Rate Effects on Foam Core

- ASTM C273 core shear tests should be performed in the compression configuration, since the tension configuration introduces peeling stresses.
- Continued analysis of the C393 beam bending tests at the slamming strain rate is recommended due to variation of the strain rates over the short duration of the test.
- A classical lamination theory module could be added to the foam core mechanics model to compute strength and stiffness values of the skins. This would allow designers to change one lamina in a layup instead of having to use a different program to recalculate the whole laminate.
- The effects of strain rate and temperature on the skins could be incorporated into the foam core mechanics model to improve the results if test data were available.
- The effect of tension and compression of the core (including non-linear stress-strain relationships) could be incorporated into the foam core mechanics model to improve the results if test data were available.

4.2.3 Impact Testing of Sandwich Laminates

- Increase coupon size to 10-times the diameter of the Tup to minimize edge effects.
- Change the interleaved material from stitched to woven to improve penetration resistance.
- Investigate the effect of other interleaved materials on the impact response of the sandwich coupons (i.e. Kevlar, carbon, Innegra).
- Conduct tests to determine interleaved laminate response to other types of loading (i.e. tension, compression, shear, flexure, & fatigue).
- Implement impact testing of a laminate designed for a small craft that incorporates Kevlar.

The results of the investigations undertaken in this project should lay the groundwork for sandwich laminate configurations with superior impact resistance and reliability. In addition, a clearer understanding of the inspection and design requirements will aid in the implementation of polymer foam cored composite sandwich constructions into naval hull designs.

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References

1. Melrose, P., Lopez-Anido, R., & Muszyński, L. (2004). Elastic Properties of Sandwich Composite Panels using 3-D Digital Image. *SEM XI International Congress and Exposition on Experimental and Applied Mechanics.* Costa Mesa, CA: Society for Experimental Mechanics.
2. El-Chiti, F. (2005). Experimental variability of e-glass reinforced vinyl ester composites fabricated by VARTM/SCRIMP. Thesis (M.S.) in Mechanical Engineering. University of Maine.
3. Fayad, G. N. (2005). Probabilistic Finite Element Analysis of Marine Grade Composites. Thesis (M.S.) in Civil Engineering. University of Maine.
4. Cain, J. J., Post, N. L., Lesko, J. J., Case, S. W., Lin, Y., Riffle, J. S., & Hess, P. E. (2006). Post-Curing Effects on Marine VARTM FRP Composite Material Properties for Test and Implementation. *Transactions of the ASME, 128*, 34-40.
5. Speckart, J. R. (2007). Five and One Year Load Spectra for Composite Fatigue Studies. s.l. : Virginia Tech.
6. Marquis, J. (2009). *Infusing Large (up to 140ft) Composite Vessels: R&D to reduce technical Risk, AEWC Report 10-47.* University of Maine. Orono: AEWC Advanced Structures and Composites Center.
7. Berube, K. A., & Lopez-Anido, R. A. (2010). Variability in the Material Properties of Polymer Matrix Composites for Marine Structures. *Journal of ASTM International, 7*(4).
8. Blake, S. P., Berube, K. A., & Lopez-Anido, R. A. (2011). Interlaminar fracture toughness of woven E-glass fabric composites. *Journal of Composite Materials*. 10pp.
9. Nader, J. W., Dagher, H. J., & Lopez-Anido, R. A. (2011). Size effects on the bending strength of fiber-reinforced polymer matrix composites. *Journal of Reinforced Plastics and Composites, 30*(4), 309-317.
10. Downs-Honey, R., Edinge, S., & Battley, M. (2005). Slam Testing of Sandwich Panels. International SAMPE Symposium and Exhibition, SAMPE 05: New Horizons for Materials and Processing Technologies, v 50, p 2807-2821.
11. Battley, M. A., & Lake, S. (2007). Dynamic Performance of Sandwich Core Materials. *16th International Conference on Composite Materials.* Kyoto, Japan.
12. Lake, S., Eaglen, M., Jones, B., & Battley, M. (2007). Slamming of Composite Yacht Hull Panels. *18th Chesapeake Sailing Yacht Symposium.* Annapolis, MD.
13. Tagarielli, V. L., Deshpande, V. S., & Fleck, N. A. (2008). The high strain rate response of PVC foams and end-grain balsa wood. *Composites: Part B, 39*, 83-91.
14. Jiang, D., & Shu, D. (2005). Local displacement of core in two-layer sandwich composite structures subjected to low velocity impact. *Composite Structures, 71*, 53-60.
15. Weeks, C. A., & Sun, C. T. (1994). Multi-core composite laminates. *Journal of Advanced Materials, 25*(4), 28-37.
16. Ratcliffe, C. P., Crane, R. M., Heider, D., Yoon, M., & Gillespie, J. W. (2001). *Structural Integrity and Damage Evaluation Routine (SIDER) for Quality Control and Health Monitoring of Structures.* Carderock Division Naval Surface Warfare Center, Survivability, Structures And Materials Directorate, West Bethesda.
17. ASTM-International. (2007). ASTM C273/C273M-06 Standard Test Method for Shear Properties of Sandwich Core Materials. West Conshohocken, PA.

18. ASTM-International. (2007). ASTM D3039/D3039M-07 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials. West Conshohocken, PA.
19. ASTM-International. (2001). ASTM D6641/D6641M-01 Determining the Compressive Properties of Polymer Matrix Composite Laminates Using a Combined Loading Compression (CLC) Test Fixture. West Conshohocken, PA.
20. ASTM-International. (2006). ASTM C393/C393M-06 Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure. West Conshohocken: ASTM-International.
21. ASTM-International. (2007). ASTM D7136/D7136M-07 Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop-Weight Impact Event. West Conshohocken, PA.
22. ASTM-International. (2008). ASTM E178-08 Standard Practice for Dealing with Outlying Observations. West Conshohocken, PA.
23. American Bureau of Shipping. (2004). *Guide for Building and Classing Naval Vessels.* New York: ABS Americas, Part 1, Ch. 4, Sec. 2-2.5.
24. Blake, S. (2010). *Crack Propagation in Secondary Bonded FRP Composite Joints.* Orono, Maine: Thesis (M.S.) in Civil Engineering, University of Maine.
25. Lesko, J., & Case, S. (2009). *Multifunctional Composites for Next Navy Seaframes.* AEWC Report 10-10.
26. Mandell, J., Samborsky, D., Wahl, N., & Sutherland, H. (2003). Testing and Analysis of Low Cost Composite Materials Under Spectrum Loading and High Cycle Fatigue Conditions. *ICCM-14.* July 14-18, 2003. San Diego, California: Society of Manufacturing Engineers.
27. Krueger, R., & O'Brien, T. (2001). A shell/3D Modeling Technique for the Anlyisis of Delaminated Composite Laminates. *Composites: Part A*, 25-44.
28. Ferrie, C. H., & Rousseau, C. Q. (2001). A Method of Applying VCCT to Corner Crack Nodes. *Proceedings of the American Society for Composites Sixteenth Technical Conference; September 9-12, 2001, Virginia Tech,.* Blacksburg, Virginia: American Society for Composites.
29. Krueger, R. (2004). Virtual Crack Closure Technique: History, Approach, and Applications. *Applied Mechanics Reviews, 57*(2), 109-143.
30. Det Norske Veritas. (2003). Rules for Classification of High Speed, Light Craft and Naval Surface Craft. Høvik, Norway: Det Norske Veritas.
31. Greene, J. (1975). Why is White so Sacred? - Energy absorption &. color in fiberglass. *Soaring*(September), 22-23.
32. Davies, J. (2001). *Lightweight Sandwich Constructions.* Malden, MA: Blackwell Science Ltd.
33. ASTM-International. (2000). ASTM C393-00 Standard Test Method for Flexural Properties of Sandwich Constructions. West Conshohocken: ASTM International.

Appendix A
Impact Test Report

COMPOSITE PANEL IMPACT TEST REPORT

BY

Hodgdon Defense Composites, LLC

For

Office of Naval Research

Contract FY-09 (N00014-10-C-0037)

Submitted

November 15, 2011

Written by: Christopher J. Duncan, Yacht Designer, Hodgdon Yachts Inc.

ACKNOWLEDGMENTS

Thanks to Hodgdon Yachts Composite group and Systems group for their efforts in the manufacture of the impact test coupons and testing apparatus.

Also a Special thank you to Kevin Houghton of Hodgdon Yachts Design and Engineering for his vision and guidance in developing the Impact Test.

ABSTRACT

Hodgdon Defense Composites conducted cored composite panel coupon impact testing in accordance with the Office of Naval Research contract (N00014-10-C-0037) task 3.3.

The object of this testing program was to investigate the impact resistance of cored carbon fiber laminations suitable for use in naval small craft hull construction. The cores were interleaved with a layer of E-Glass located as described below.

Impact testing was conducted utilizing guidance from ASTM D7136/D7136M *Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop Weight Impact Event*.

A 0.625 inch diameter impactor (tup) with a hemispherical tip was impacted against the test coupons at six different energy levels ranging from 61 to 147 FT-Pounds (83 to 198 Joules) at velocities from 13 feet/second (3.9 meters/second) to 18 feet/second (5.4 meters/second). Initially all samples selected were impacted with the 0.625 inch diameter impactor.). Based on comments from ONR, a 2 inch diameter impactor was fabricated and testing began on the remaining samples. The energy levels were increased to 299 to 1002 Ft-Pounds (406 to 1361 Joules) with velocities from 22 feet/second (6.7 meters/second) to 25 feet/second (7.6 meters/ second.

Four different interleaving variations were tested with ELTM 1608 E-Glass interleaving, (appendix C page 25). The interleaving on the A group is next to the impacted (top) skin. On the B group the interleaving is near the top skin, On the C group the interleaving is at the mid core location and the D group interleaving is near the bottom skin, (appendix C page 25). The intention was to determine if the positioning of the interleaving affected the results on the total impact resistance of a specific laminated sample, in addition, higher density cores were used in laminate groups 2, 3 and 4 in order to address questions of impact resistance of higher density core materials.

Failure is defined when both skins and the core were visibly breached by the impactor such that moisture could pass through the sample in line with the path of travel of the impactor.

380 coupon samples were tested with the 0.625 inch diameter impactor, where 73 coupon samples matched the failure definition. Of these coupons, samples from configuration 'A' had fewer failures and the highest failure thresholds. See Table 1 (p15) for the distribution of failures

, 285 coupon samples were tested with the 2 inch diameter impactor, where 47 coupon samples matched the failure definition. Of these coupons, samples from configuration 'B' had less failure rates and highest failure thresholds. See Table 2 (p16) for the distribution of failures.

Testing with the 2 inch impactor showed that the damage to the interior areas of the coupon samples had significantly more propagation of damage than that of the 0.625 inch diameter impactor. The 0.625 inch diameter impactor caused very local damage to the foam core and interleaving while the 2 inch diameter impactor caused widespread damage radiating away from the tip of the impactor.

Energy levels to cause failures using the 2 inch impactor were 6 times that of the 625 inch Impactor.

In both the 0.625 and 2 inch diameter series of test where failure did occur, the foam core compacted in line with the tip of the impactor and was then forced through underlying laminate material by the impactor (see fig 5 and fig 6 p. 8).

EXECUTIVE SUMMARY

Hodgdon Defense Composites investigated the impact resistance of cored carbon fiber laminations suitable for use in naval small craft hull construction. The cores were interleaved with an E-Glass layer utilizing four locations within the core.

Impact testing was conducted utilizing guidance from ASTM D7136/D7136M *Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop Weight Impact Event* . *A* 0.625 inch diameter impactor with a hemispherical tip was impacted against the test coupons at six different energy levels ranging from 61-147 FT-Pounds (83-198 Joules) at velocities from 13 feet/second (3.9 meters/second) to 18 feet/second (5.4 meters/second). A 2 inch diameter impactor was then impacted on the remaining samples with increased energy levels to 299 to 1002 Ft-Pounds (406 to 1361 Joules) and velocities from 22 feet/second (6.7 meters/second) to 25 feet/second (7.6 meters/ second).

Failure of a test coupon is defined when both skins and the core are visibly breached by the impactor such that moisture can pass through the damage caused by the impactor.

For the purpose of this initial testing, only H100 Cored panels with ELTM 1603 interleave material were evaluated for optimal interleaving location placement for the impact resistance performance characteristics.

During testing with the .625 inch diameter impactor 19% coupons tested achieved failure, the best performing coupon configuration was the A base line panel (Table 1 p 15)

During testing with the 2 inch impactor 17% of coupons tested achieved failure. Of the panels tested the B configuration showed the best performance (Table 2, p16).

In addition to evaluation of interleave locations, tests were conducted to consider if increasing core densities resulted in increased impact resistance.

In all testing cases, the higher density cores were more resistant to penetration.

Most panels tested with the 2 inch impactor have cracks on the top surface extending to the edge of the panel as shown in Fig 12 and 13 (p.16).

It is recommended that future testing be done on coupons that have overall unsupported dimensions of 10 times the impactor diameter to possibly reduce the edge effects.

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LIST OF SYMBOLS & ABBREVIATIONS

Avg. = Average

AEWC=Advanced Engineered Wood Composites Center at the University of Maine, Orono Maine

E= Energy in foot pounds and joules in SI

ETC= Et Cetera,

g=gravitational constant (32 ft/sec^2)

H= Drop height in feet and decimals

HDC= Hodgdon Defense Composites, LLC, P.O. Box 15025 Portland Maine 04112

HSB=Hodgdon Ship Building, 14 School St. East Boothbay, Maine 04544

HYI=Hodgdon Yachts Inc. 14 School St. East Boothbay, Maine 04544

IAW= in accordance with

ITA=Impact Testing Apparatus

M= Mass of object in Mass pounds

ONR= Office of Naval Research,

QA= Quality Assurance

StMDev = Standard Mean Deviation

$t_{1=}$ Time measured for Impact Testing apparatus carriage optical gate flag to travel 1 inch.

V= Velocity in feet per second

LIST OF FORMULAE

$$E = \frac{MV^2}{2}$$ In foot/pounds

Where:

E= energy (Pound/Feet)

M =Mass (pounds mass)

V=Velocity (Feet/second)

$$E = \frac{MV^2}{2} * 1.355818$$ In Joules

Where:

E= energy (Joules)

M =Mass (pounds mass)

V=Velocity (Feet/second)

$$M = \frac{W}{g}$$

Where:

M=Mass (pounds mass)

W= Measured Weight (pounds)

g= gravity constant (32ft/sec^2)

$$V = \frac{1}{12}/t_1$$

Where:

V=Velocity (feet/second)

t_1=Measured time for one inch of travel

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DEFINITIONS

Bottom of coupon: The non-molded side of the coupon sample, characterized by the rough surface of the skin. This surface replicates the interior hull skin of a vessel.

Carriage weights: Steel weights added to the impact testing apparatus in order to increase the energy levels delivered to the test coupon.

Cobble: A rounded stone roughly 3 inches in diameter, typically found imbedded in the shore material and partially exposed on waterfront beaches and shorelines.

Coupon Impact Deformation: Deformation that occurs as a result of impacting the test sample but may not be from direct contact with the impactor, examples include skin wrinkling, blistering and surface delamination

Coupon Impact Failure: When the bottom skin surface has shown visible damage to an extent that measurable amounts of moisture that are detectable without special instruments, can travel from the top skin area of a coupon panel past the bottom skin, of the same panel following a path through the core of the panel created by the impactor.

Coupon orientation: The orientation of the test coupon in the Impact testing apparatus as clamped in place for testing, generally with the 0 degree fiber orientation being fore and aft in relation to the operational access opening of the impact testing apparatus base clamping area.

Coupon Sample: The 10 inch by 10 inch representative portion of a composite lamination that is used for testing in the Impact Testing Apparatus.

Failure of test coupon: When both skins and the core were visibly breached by the impactor such that moisture could pass through the damage caused by the impactor.

Failure Threshold: The energy required to produce failure in at least 80 percent of samples tested at a given energy level

Impact energy: The energy delivered to the top surface of the test coupon by the hemispherical tip of the impact impactor, measured at about 0.25 inches from impact utilizing the formula for Energy as shown on page 8.

Impact testing apparatus base: The area that supports the Impact Testing Apparatus and contains the panel test coupon clamping mechanism which consist of a ground stainless steel plate and four table type clamps.

Impact testing apparatus carriage: The aluminum frame in which the impactor adapter and impact testing apparatus guide rails are attached and is capable of carrying various weight amounts. It is equipped with two secondary impact preventers (braking devices) to prevent secondary impact damage to a test sample.

Impact testing apparatus drop height: The height at which the impactor is dropped in order to produce the desired energy level for a given carriage weight, the height is measured form the top surface of the test coupon to the tangential tip of the impactor.

Impact testing apparatus optical gate: An electro-optical timing device for the determination of velocity within 0.25 inches of impactor impact on the test sample.

Impact testing apparatus timing flag: An attachment to the carriage that has two light blocking panels with an opening between them precisely 1 inch in distance from edge to edge and is passed through the optical gate during carriage travel in order to establish time of travel for velocity equations.

Impact testing apparatus: That device or machine that provides a means of delivering repeatable impacting events in which a impactor attached to a weighted carriage is dropped vertically onto a test sample attached to the Impact testing apparatus base.

Interleaving: A single skin laminate that is bonded between two outer skins of a composite cored panel, usually with core material between the interleaving and the outer skins of a panel.

Laminate fiber orientation: The orientation of the fibers in each layer of the test sample skin laminations.

Maximum travel scale: A sliding scale attached to the impact testing apparatus that is pushed along its track during the final 4 inches of impact testing apparatus carriage travel and is used to determine to full distance traveled of the impactor

Panel deflection indicator: A hydro-mechanical device consisting of a telescoping tube that slides when a force is acted upon it and remains at its closed location by the action of a damping medium in order that a measurement may be taken to determine its full travel distance.

Panel: The parent composite lamination that the coupon samples are cut from.

Top of coupon: The molded surface of a test coupon sample characterized by a smooth surface, the top surface is the first surface to be impacted during testing. This surface replicates the exterior surface of the hull skin.

Impactor: The penetrator or impactor that is attached to the impactor adapter and is impacted against the testing sample, typically the contact surface is highly polished and has a hemispherical tip.

Impactor adapter: That device that attaches to the underside of the impact testing apparatus carriage and makes it possible to distribute the high energy forces throughout the carriage assembly in order to prevent damage to the carriage. The impactor adapter has a standard female thread that facilitates easy changing of the impactor without testing apparatus measurement re-calibration

Impactor Collar: A fiberglass ring that slides over the impactor and during impact is slid along the impactor by the top surface skin in order to comparatively check the impactor penetration depth with the sliding scale.

Impactor tip: That point on the tangential tip of the hemispherical portion of the impactor that is directly in line with the direction of travel and is the first point of contact with the test samples top skin or surface.

INTRODUCTION

Composite hull construction on small and large watercraft has been an industry norm for several years now. The light weight and strength make this type of construction very marketable to government programs for future naval craft. However there is only a small amount of data concerning the impact resistance of foam cored composite laminate hulls. This lack of good data on such a construction method is unfortunate because smaller naval craft under 120 ft may be used to assault a beachhead or landing and on that beachhead or landing may be cobbles that could puncture the skins of the hull and render the craft unusable and unable to continue its mission. Designers and builders of these types of naval craft need a thorough understanding of the limitations of low speed impact resistance of the cored laminates used in constructing these hulls.

In an effort to understand and quantify the low speed impact resistance of composite panels, Hodgdon Defense Composites has designed a test based on ATSM standard D7136/D7136M. The Testing consist of dropping a guided weighted impactor against sample coupons from 11 different laminate configurations in order to comparatively observe and document the damage to the samples based on a baseline test sample configuration. In each group of sample laminate configurations there is an interleaving layer that has its location in the laminate stack depending on the desired test group properties. In the base samples the material for the interleaving is attached to the underside of the top skins, in the second group the interleaving material is located 25% of the thickness of the core from the top skin of the sample, in the third group the interleaving material is located half way, and in the fourth group the interleaving material is located 75% the thickness of the core from the top skin, (Table 4 p21).

A laminate configuration of high density core materials was also constructed in order to determine what effect the core material had on low speed impact resistance.

TESTING DETAILS

OBJECTIVES

The main object of this test was to develop an approach to evaluate impact damage at the component scale.

TEST METHODS

Impact testing of the composite coupon samples was carried out in accordance with guidance from ASTM Standard D7136/D7136M.

The Testing was modified from ASTM Standard D7136/D7136M in order to accommodate testing of the cored composite panel coupons. The testing was modified by measuring the penetration depths with an independent measurement scale and impactor collar, measurements were made to the nearest 0.0312 inch. Penetration depth was determined by subtracting the test coupon deflection from the full downward travel of the impactor. In addition ASTM Standard D7136/D7136M was modified by the addition of weight to the Impact testing apparatus in order to increase the energies needed to produce panel impact failure.

Task: Impact Testing of Composite Panels Utilizing Hodgdon Defense Composites Impact Testing Standards (p20) based on guidance from ASTM D7136/D7136M.

Conditions: Impact testing were conducted indoors at Hodgdon Shipbuilding's Murray Hill facility in East Boothbay, Maine utilizing the Hodgdon Defense Composites (HDC) designed and constructed Impact Testing Apparatus (ITA) in order to evaluate the impact resistance of Composite Panel constructed with various laminate configurations and materials as specified by the Office of Naval Research (ONR).

Scope: HDC impact testing standards are modeled after ASTM Standard D7136/D7136M and to be reported as ASTM non-standard testing utilizing HDC Impact Testing Report Electronic Form HDC 10.03.1

Data collection utilized the HDC Impact Testing Field Report Form HDC 10.03.2. (Table 3, p6).

Drop Height measurements are measured in decimal inches to two places.

All Coupon sample linear measurements are in decimal inches to three places.

All weights are measured in decimal pounds to three places.

All forces are calculated in decimal foot pounds (Joules)

All velocities are measured in decimal inch/sec to two places and calculated to decimal feet/ sec to two places.

Temperature is in Degrees Fahrenheit.

Barometric pressure is measured in inches of mercury.

Date time was recorded as eastern daylight saving time (East Boothbay, Maine) in a 12hr cycle in the MM/DD/YY HR: Min AM/PM.

The original HDC 10.03.2 for each coupon tested is maintained in a dedicated binder at Hodgdon Defense Composites Murray Hill Facility office for future reference.

A printed copy of HDC 10.03.1 for each test group is kept in the HDC 10.03.2 dedicated binder at Hodgdon Defense Composites Murray Hill Facility office.

Photographs and or Videos are kept on the Hodgdon Defense Composites Murray Hill Facility office server hard drive and numbered with the same number as the specimen ID followed by the sequence number of the particular photograph of the specimen.

Variations to ASTM D7136/D7136M Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop Weight Impact Event as defined by HDC testing standards are:

1. The panel thicknesses are 1.68 inches and are of laminated core construction with a layer of interleaving between the outside skins.
2. The Carriage weighs more than the 5kilograms suggested weight as outlined in ASTM Standard D7136/D7136M, Paragraph (7.3.1).
3. Impact depth will be measured using a sliding Impactor collar with a graduated scale scribed on the impactor.

After initial testing with the .625 inch Impactor, subsequent testing was done with a 2 inch diameter impactor.

TESTING APPARATUS

An impact testing machine was designed and built by HDC utilizing guidance from ASTM Standard D7136/D7136M (Fig 5, p9). See appendix D through I starting on page 25.

The apparatus is constructed of pultruded composite angles and channels. Two T guide rails are installed on the inside surfaces of the vertical C channels. A Carriage is attached to the T rails via four "Drylin" by IGUS sliding bearings, the carriage is constructed of aluminum sheet with a steel reinforcing plate installed at the bottom inside surface, accommodations were made for the addition of steel weights in order to increase the energy delivered through the stainless steel hemispherical impactor spike or impactor. The carriage has installed a kinetically activated braking system (Fig 8, p9), which prevents secondary impacts to the test sample. The impactor is attached to the carriage with a impactor adapter; this allows the interchanging of various sized impactor without time consuming recalibration of the optical gate.

The base of the testing apparatus is a concrete pad with a 10 inch by 10 inch square hole, on top of which, is bolted a stainless steel test sample coupon support pad 12 inches by 12 inches by .5 inches thick with an 8 inch by 8 inch square hole cut into the center. On two opposite sides of the coupon support pad are sample guide fiddles with two table clamps attached. The forward side of the support pad has installed two guide pins to assist in the placement of the test sample.

The Testing Apparatus carriage is raised to the desired height with a halyard attached to a crossbar trigger assembly. Desired drop height is the drop height from the hemispherical strike tip of the impactor to the top surface of the test sample and is read via a calibrated graduated scale on the right vertical channel.

Release of the carriage for freefall is accomplished with a simple block and pawl trigger mechanism attached to a lanyard that is then lead parallel with the halyard to the operator for employment, this allows smooth even release of the carriage without imparting any horizontal movement that may cause excessive friction (Fig 10, p10).

The impactor is made of stainless steel (hardness rating 60). The 2 and 3 inch impactors have engraved witness marks graduated by .0625 inches distance. Current impactor diameters are: .375 inches, 0.625 inches, 1 inch, 1.5 inch, 2 inch and 3 inch. All impactors are the same length from the shoulder to the hemispherical tangential tip in order to minimize recalibration of the Impact Testing Apparatus optical gate and carriage timing flags (Fig12, p10).

Within the well of the concrete base a deflection gauge is placed to measure the deflection of the panel during an impact event, the gauge is a mounting base and a vertical G-10 tube filled with grease. The tube has a relief hole drilled into the bottom side and within this tube is a smaller diameter tube that is set to the height of the face of the bottom of the test sample and measured from the top of the smaller tube to the top shoulder of the larger, after impact the gauge is again

Base plate

The base of the testing apparatus is a concrete pad with a 10 inch by 10 inch square hole, on top of which, is bolted a stainless steel test sample coupon support pad 12 inches by 12 inches by .5 inches thick with an 8 inch by 8 inch square hole cut into the center. On two opposite sides of the coupon support pad are sample guide fiddles with two table clamps attached. The forward side of the support pad has installed two guide pins to assist in the placement of the test sample.

14.5 inches wide x 14.5 inches long x .5 inches thick with a centered square cutout of 8 x 8 inches.

Coupon clamping is provided via 4 table clamps with a rubber tip, the maximum clamping force of the table clamps is at least 200 pounds, however minimal clamping pressure was exerted for this testing. The clamps were located on the right and left side of the sample, two to a side.

Instrumentation is provided with a photo gate sensor timer with the ability to time consecutive events in order to provide times for velocity calculations. The stop time will be triggered when the impactor is no further away than 0.25 inches from the strike point of the coupon.

Minimum and maximum drop heights, the minimum drop height of the impactor is 36 inches and the maximum drop height is 126 inches from strike tip of impactor to top of base plate and 124.5" from strike tip of impactor to top of 1.5" panel.

Impact testing apparatus impactor carriage

The Testing Apparatus carriage is raised to the desired height with a halyard attached to a crossbar trigger assembly. Desired drop height is the drop height from the hemispherical strike tip of the impactor to the top surface of the test sample and is read via a calibrated graduated scale on the right vertical channel.

Release of the carriage for freefall is accomplished with a simple block and pawl trigger mechanism attached to a lanyard that is then lead parallel with the halyard to the operator for employment, this allows smooth even release of the carriage without imparting any horizontal movement that may cause excessive friction (Fig 10, p10).

The Initial weight of free falling carriage and guides was recorded. Before initial testing began the impactor carriage was weighed to the nearest decimal pound.

Addition of weights, addition weights may have been added to the impactor carriage when an increase in impact energy was required, each weight slab did have its weight verified before placement into the carriage weight tray.

Carriage secondary impact mechanism, the carriage secondary impact preventing mechanism is inspected prior to each drop event, at a minimum the inspection did include removal of contaminates on the rubber wheels, rails and a check for broken or missing items.

Impact testing apparatus impactor

The impactor is made of stainless steel (hardness rating 60). The 2 and 3 inch impactors have engraved witness marks graduated by .0625 inches distance. Current impactor diameters are: .375 inches, 0.625 inches, 1 inch, 1.5 inch, 2 inch and 3 inch. All impactors are the same length from the shoulder to the hemispherical tangential tip in order to minimize recalibration of the Impact Testing Apparatus optical gate and carriage timing flags (Fig12, p10

Impactor design style, length, diameter, tip style, the impactor is designed of 316 S.S. which is then highly polished to limit any drag of friction when the test coupon is penetrated. The Tip is a hemispherical tip of 0.625 inches diameter as specified in the ASTM Standard D7136/D7136M. (Fig 12, p10).

Impactor preparation for testing: cleaning, check for straightness, was conducted at the beginning of each test day.

Within the well of the concrete base a deflection gauge is placed to measure the deflection of the panel during an impact event, the gauge is a mounting base and a vertical G-10 tube filled with grease. The tube has a relief hole drilled into the bottom side and within this tube is a smaller diameter tube that is set to the height of the face of the bottom of the test sample and measured from the top of the smaller tube to the top shoulder of the larger, after impact the gauge is again

Lubrication of the impactor was conducted for each test sample to be impacted, lubrication of the impactor was provided by application of wax from a wax paper lubricator.

Impactor storage: At the end of the testing period the impactor was cleaned with a clean rag and water, dried and lightly oiled then returned to the storage area at the Hodgdon Defense Composites Murray Hill Facility office. The Carriage was then hoisted to the locking position and secured with a bicycle type chain lock to prevent unauthorized usage.

Variations to impactor design:

Variations to the impactor design were made utilizing the impactor adapter threads and bearing surfaces to the best extent possible.

measured in order to determine the actual deflection of the panel. This measurement is subtracted from the full travel of the carriage for actual indentation depth measurements.



Fig 7. Overall view of the Impact Testing Apparatus

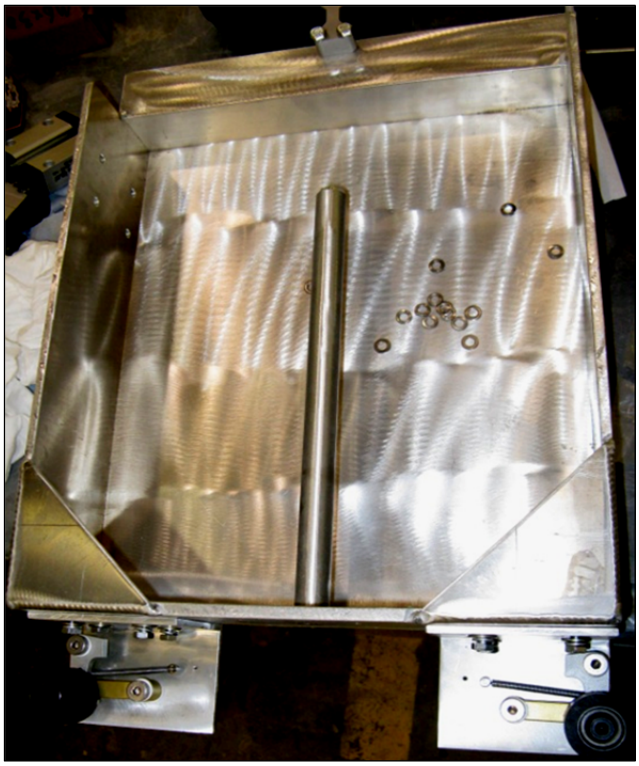


Fig 8. Impact Testing Apparatus Carriage



Fig 9. Secondary bounce brake assembly

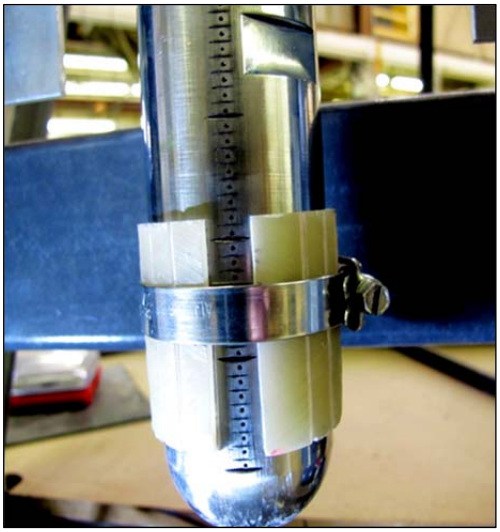


Fig 10. 2 inch impactor with engraved markers and depth collar

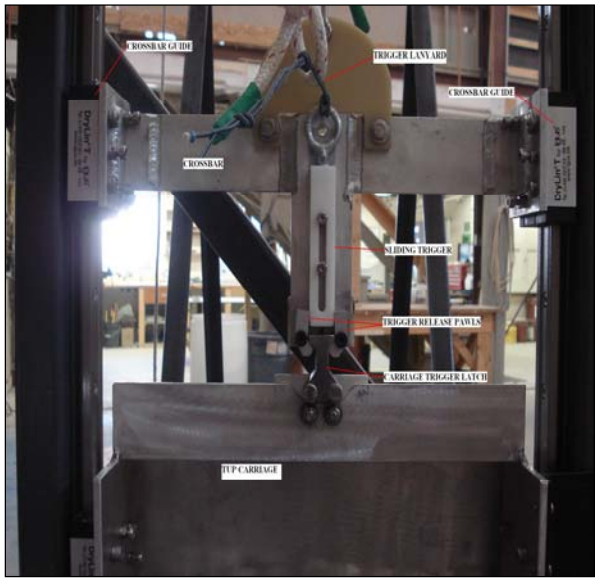


Fig 11. Crossbar and Trigger Assembly

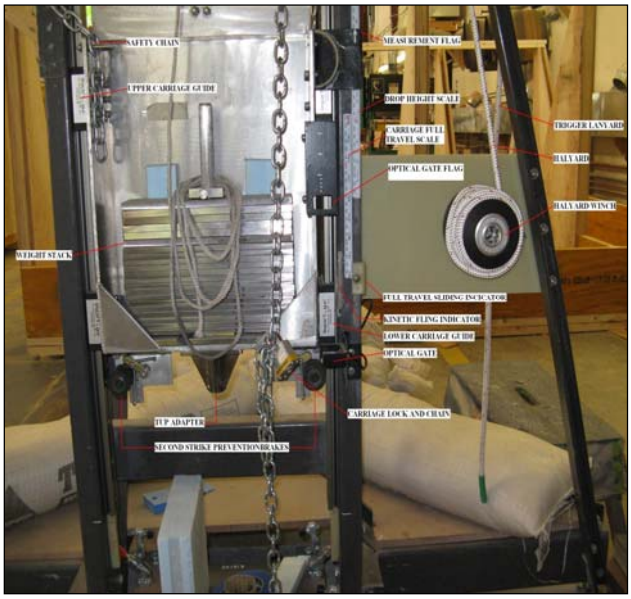


Fig 12. Overview of working components



Fig 13. From left to right- 0.375, 0.625, 1, 1.5,2,3 inch impactors

TEST COUPONS

See appendix C (p25) for QA sheets for each Panel construction.

The resin used in all coupons was Proset LV117 with a Proset 237 hardener.

The Test Panels were cut to 10 inch by 10 inch Test Sample Coupons for standardization and fit to the ITA base.

The Test Sample Coupons were an average of 1.68 inches thick.

Test panel coupon sample configurations were laminated at HSB facility as outlined in the ONR testing sample laminate schedule (Table 4, p21). The utmost care and quality control was provided in the construction of the panels to insure continuity throughout the test samples.

Naming conventions:

Test coupon samples were numbered in such a way that identifies what configuration and panel the coupon sample came from and sequentially in relation to the other coupon samples from the same panel. Each sample coupon also has a Laminate Rose noting the 0/90 orientation and the molded side of the coupon (Fig.2, p.7).

Example: 3 panels were made to configuration D2; the selected coupon came from the second panel made which was cut into 20, 10”inch x 10 inch square coupons. The selected coupon is the fourth coupon cut from this panel. Therefore the naming of this panel is: D2 (2)-4

Coupon Preparation for Testing:

Test Samples were cut to size, marked and stored at the testing location at least 24 hr prior to testing to insure the panels are acclimated to the testing location, each specimen was then inspected visually to insure there are no unknown defects prior to testing. Prior to testing but after the 24 hour acclimation period, the panel was measured in width, length and thickness as outlined in the ASTM D7136/D7136M standard and noted on HDC form 10.03.2 (Table 3, p6).

Data Collection and Reporting:

Data was collected on site during testing, each test coupon was measured in width and lengths as well as thickness of the panels in order to insure basic test sample coupon design parameters were met. Then the measurements were recorded on HDC Form 10.03.2. Then each sample was placed in the Impact testing apparatus base area and clamped in place with the impact testing apparatus coupon table clamps. After an inspection of the impact testing apparatus and test coupon the carriage was raised to the desired drop height and released. After the impactor impacts the panel and all motion has stopped the carriage is then secured against any further movement. The Optical gate time is recorded as taken from the optical gate timer and annotated on the HDC form 10.03.2. The impactor collar was then observed for signs of top skin deflections and or bounce of the impactor. The next observation was made to the impactor full travel scale and compared to the kinetic indicator to insure that the travel distance was accurate. Measurements were taken using a standard caliper with an accuracy of 0.0001. In some select cases the coupon was then cut in two using a band saw in order to record and observe the interior damage to the coupon. The data collected includes the following:

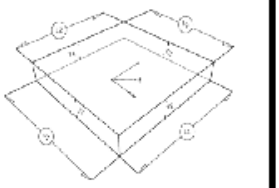
1. Specimen ID
2. Test date
3. Air temperature
4. Barometric pressure
5. humidity
6. Width of test coupon
7. Length of test coupon
8. Thickness of test coupon
9. Drop height of Impactor
10. Optical gate time
11. Carriage weight
12. Damage in the 0 degree direction
13. Damage in the 90 degree direction
14. Damage to the bottom skin of test coupon
15. Full downward impactor travel from top surface of static test coupon
16. Panel deflection from bottom skin of static test coupon to bottom skin of coupon acted on by full impact energy.
17. Photographs of each sample and bottom skin damage if applicable.

Impact Testing Report Form

HDC FORM 10.03.2	HODGDON DEFENSE COMPOSITES IMPACT TEST DATA COLLECTION REPORT				PAGE 1 OF___
DATE:	AIR TEMP:	BARO PRESSURE:	HUMIDITY:	CONFIGURATION:	SPECIMEN ID:
NAME OF RESEARCHER:					

VARIATIONS TO TESTING:

IDENTIFICATION OF CONSTITUENT INFORMATION:



INSTRUMENT	CALIBRATION DATE	METHOD OF CALIBRATION	CALIBRATION TECH
OPTICAL GATE VELOCITY METER:			
MICROMETER:			
CALIPER:			
WEIGHT SCALE:			

	COUPON								TEST				DAMAGE			
SPECIMEN ID	WIDTH 1	WIDTH 2	LENGTH 1	LENGTH 2	THICKNESS 1	THICKNESS 2	THICKNESS 3	THICKNESS 4	DROP HEIGHT	TIME C1	TIME C2	CARRIAGE ADD LWT	DAMAGE W 0°	DAMAGE W 90°	INDENTATION DEPTH	PICTURE OR VIDEO NUMBER

Fig. 14 .Impact Test Report.

Calculated results of each group of test specimens are annotated on HDC electronic form 10.03.1 and are made available for inspection.

PHOTOGRAPHS VIDEO

At minimum, a digital photo was taken of each test coupon after the impactor had impacted the sample. The photograph was taken in a top view orientation with the "0" axis of the coupon oriented to the top of the photo. There are selected samples that were bisected and each half is also photographed in order to document internal damage.



Fig 2. Typical top view photo.

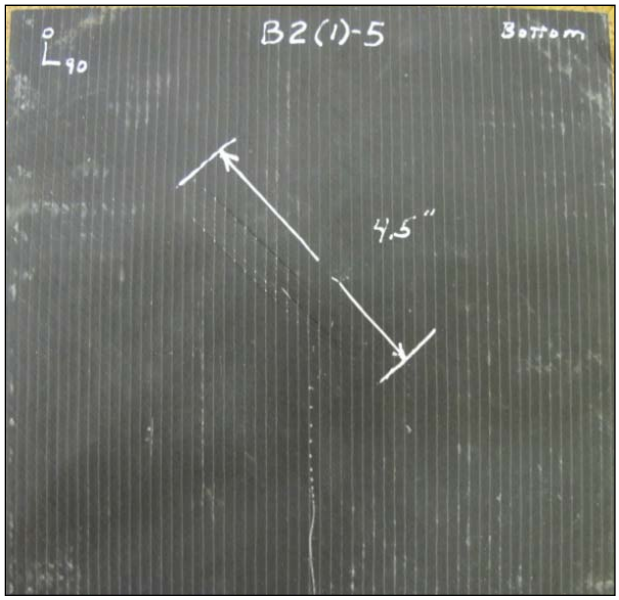


Fig 3. Typical linear failure.

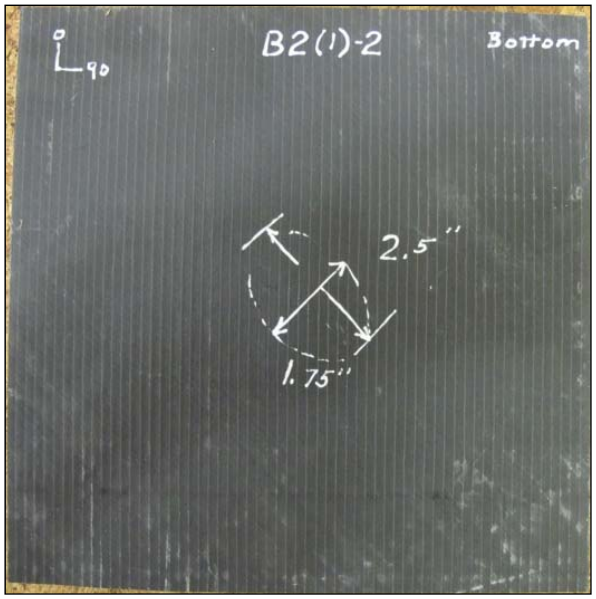


Fig 4. Example two directional failure.



Fig 5. Bisected samples showing internal damage from a 0.625 inch impactor.



Fig 6. Bisected samples showing internal damage from a 2 inch impactor and close up of interleaving damage.

Video shorts are kept on the HDC server and are available on request.

DATA ANALYSIS

Calculations for the determination of the energy delivered were base on the E= (MV^2)/2 formula. The Impact testing apparatus utilizes an optically triggered timing device that is capable of computing time in the mille-second. In order for the optical gate to calculate time of travel two optical events must occur in which two flags must break the beam in order to give enough events to calculate the time. In our case we used a flag that was attached to a carriage in such that the flag had two light blocking panels. The open distance from the edge of the first encountered panel to the edge of the second encountered panel is precisely 1 inch therefore the optical gate timing device displayed time indicates measurements for 1 inch travel. This time/distance traveled was then converted to ft/sec traveled for use in the energy formula. The measured timing event was triggered to within 0.25 inches of the impactor striking the top surface of the specimen.

In order to determine the failure of a panel the panel was visually inspected after impact for signs of cracking and splitting on each surface and along the edges of the panel especially where the outer skins and core bond joint. The panel was then marked with either a straight line dimension line indicating to what extent the cracking propagated or with a circular marking showing the extent of serious blistering of the skin with a dot or line to show where the actual penetration hole is found(Figs 4 and 4, p 7). We indicated that panels that failed were to carry a 1 designation in HDC electronic form 10.03.1 then by sorting failures by panel core type we determined statistically which specimens has the least amount of failures and the energy required for the failure.

Tested samples were then analyzed by type of specimen and energy level to verify that the group had at least 80% of tested samples reach failure criteria. At this point we would then label that group as reaching failure threshold.

.625 INCH IMPACTOR ANALYSIS WORKSHEET

Panel Type	Drop Height	Weight	Avg. Fail Energy (Foot Pounds)	Avg. Fail Energy (Joules)	# Tested at specified energy level	# Failed	% Failure	est. failure at 80% by unit		
Carriage weight 26.27 pounds dropped from 5.5 feet									Ft-pounds	Joules
A	5.5	26.27	132.97	180.29	15	3	20	Greater than	133	180
B	5.5	26.27	132.91	180.20	5	2	40	Greater than		
B	5	26.27	124.16	168.34	5	4	80	Equal or greater than	124	168
B2	5.5	26.27	134.04	181.73	5	5	100	Equal or greater than	134	182
B2	5	26.27	123.10	166.91	5	2	40	Greater than		
B3	5.5	26.27	134.12	181.84	5	1	20	Greater than	134	182
B3	4.5	26.27	113.45	153.82	5	1	20	Greater than		
C	5.5	26.27	134.04	181.73	5	4	80	Equal or Greater than	134	182
C	5	26.27	123.10	166.91	5	3	60	Greater than	123	167
C	4.5	26.27	109.05	147.85	5	1	20	Greater than		
C2	5.5	26.27	135.25	183.37	5	5	100	Equal or Greater than	135	183
C2	5	26.27	122.11	165.56	5	3	60	Greater than		
C3	5.5	26.27	134.04	181.73	5	4	80	Equal or Greater than	134	182
C3	5	26.27	123.10	166.91	5	1	20	Greater than		
D	5.5	26.27	134.04	181.73	5	4	80	Equal or Greater than		
D	5	26.27	122.11	165.56	5	5	100	Equal or greater than	122	167
D	4.5	26.27	109.05	147.85	5	4	80	Equal or Greater than		
D2	5.5	26.27	134.04	181.73	5	5	100	Equal or Greater than	134	182
D2	5	26.27	122.11	165.56	5	4	80	Equal or Greater than		
D3	5.5	26.27	136.53	185.11	5	5	100	Equal or Greater than	137	185
D3	5	26.27	123.10	166.91	5	1	20	Greater than		
D4	5.5	26.27	134.04	181.73	5	5	100	Equal or Greater than	134	181
D4	5	26.27	124.16	168.34	5	2	40	Greater than	124	168

Table 1. 0.625 inch Impactor failure results

2 INCH IMPACTOR ANALYSIS WORKSHEET

	Configuration	drop height	weight	Avg Fail Energy (Foot Pounds)	Avg Fail Energy (Joules)	# Tested at specified energy level	# Failed	%			
	2" IMPACTOR FAILURES								Est. failure at 80% by unit		
BASIC INTERLAMINATE CONFIGURATIONS (IN YELLOW)	A	7	125	797	1084	5	5	100		Ft-Pound	Joules
	A	6	125	728	989	5	5	100	GREATER THAN		
	A	6	125	675	918	5	3	60		702	954
	B	10	75	760	1032	10	3	30			
	B	7	125	818	1112	1	1	100			
	B	7	125	822	1118	1	1	100	GREATER THAN		
	B	7	125	784	1066	7	5	71		784	1066
	B2	10	75	642	872	10	0	0	GREATER THAN		
	B3	10	75	733	997	5	0	0	GREATER THAN		
	C	10	75	734	998	5	1	20			
	C	7	125	764	1039	5	4	80	EQUAL OR GREATER THAN	764	1039
	C	6	125	731	993	5	3	60			
	C2	10	75	735	999	5	0	0	GREATER THAN		
	C3	7.5	125	942	1280	3	2	67	GREATER THAN	942	1280
	C3	7	125	860	1169	3	1	33			
	C3	6.5	125	778	1057	5	2	40			
	D	10	75	746	1014	5	4	80	EQUAL OR GREATER THAN	746	1014
	D2	10	75	733	996	5	3	60	GREATER THAN	733	996
	D3	10	75	739	1004	5	1	20	GREATER THAN	739	1004
	D4	10	75	721	981	5	4	80	EQUAL OR GREATER THAN	721	981

Table 2. Two inch Impactor failure results

RESULTS & DISCUSSIONS

Observations:

0.625 inch impactor

During testing with the .625 inch impactor 73 of 380 panels achieved failure criteria, Failures were as follows:

.625 inch Impact results

Configuration A

CBX 1800
CLT 1800
ELTM 1603
H100 1.5”
CLT 1800
CBX 1800

Failure Threshold 133 ft-lb
PERCENT TESTED RESULTED IN FAILURE 20%

Configuration B

CBX 1800
CLT 1800
H100 0.5"
ELTM 1603
H100 1.0"
CLT 1800
CBX 1800

Failure Threshold 124 ft-lb
PERCENT TESTED RESULTED IN FAILURE 80%

Configuration C

CBX 1800
CLT 1800
H100 0.75"
ELTM 1603
H100 0.75"
CLT 1800
CBX 1800

Failure Threshold -134 ft-lb
PERCENT TESTED RESULTED IN FAILURE 80%

Configuration D

CBX 1800
CLT 1800
H100 1.0"
ELTM 1603
H100 0.5"
CLT 1800
CBX 1800

Failure Threshold 109 ft-lb
PERCENT TESTED RESULTED IN FAILURE 80%

Configuration B2

CBX 1800
CLT 1800
H130 0.5"
ELTM 1603
H100 1.0"
CLT 1800
CBX 1800

Failure Threshold 134 ft-lb
PERCENT TESTED RESULTED IN FAILURE 100%

Configuration C2

CBX 1800
CLT 1800
H130 0.75"
ELTM 1603
H100 0.75"
CLT 1800
CBX 1800

Failure Threshold 135 ft-lb
PERCENT TESTED RESULTED IN FAILURE 100%

Configuration D2

CBX 1800
CLT 1800
H100 1.0"
ELTM 1603
H130 0.5"
CLT 1800
CBX 1800

Failure Threshold 122 ft-lb
PERCENT TESTED RESULTED IN FAILURE 80%

Configuration B3

CBX 1800
CLT 1800
ELTM 1603
H100 1.0"
CLT 1800
CBX 1800

Failure Threshold 134 ft-lb
PERCENT TESTED RESULTED IN FAILURE 20%

Configuration C3

CBX 1800
CLT 1800
H160 0.75”
ELTM 1603
H100 0.75"
CLT 1800
CBX 1800

Failure Threshold 134 ft-lb
PERCENT TESTED RESULTED IN FAILURE 80%

Configuration D3

CBX 1800
CLT 1800
H100 1.0”
ELTM 1603
H160 0.5"
CLT 1800
CBX 1800

Failure Threshold 136 ft-lb
PERCENT TESTED RESULTED IN FAILURE 100%

Configuration D4

CBX 1800
CLT 1800
M100 1.0”
ELTM 1603
H100 0.5”
CBX 1800
CBX 1800

Failure Threshold 134 ft-lb
PERCENT TESTED RESULTED IN FAILURE 100%

The average penetration depth of the impactor in panels that achieved failure criteria was 1.78 inches with a standard mean deviation of 0.156 inches. The average panel thickness is 1.68 inches. The range of Energy to cause the failures was from 147.8 Joules to 198.6 Joules, with an average energy of 174.4 Joules and a standard deviation of 10.5 Joules.

2 inch Impact results

Configuration A

CBX 1800
CLT 1800
ELTM 1603
H100 1.5”
CLT 1800
CBX 1800

Failure Threshold 728 ft-lb
PERCENT TESTED RESULTED IN FAILURE 100%

Configuration B

CBX 1800
CLT 1800
H100 0.5"
ELTM 1603
H100 1.0"
CLT 1800
CBX 1800

Failure Threshold 822 ft-lb
PERCENT TESTED RESULTED IN FAILURE 100%

Configuration C

CBX 1800
CLT 1800
H100 0.75"
ELTM 1603
H100 0.75"
CLT 1800
CBX 1800

Failure Threshold -764 ft-lb
PERCENT TESTED RESULTED IN FAILURE 80%

Configuration D

CBX 1800
CLT 1800
H100 1.0"
ELTM 1603
H100 0.5"
CLT 1800
CBX 1800

Failure Threshold 746 ft-lb
PERCENT TESTED RESULTED IN FAILURE 80%

Configuration B2

CBX 1800
CLT 1800
H130 0.5"
ELTM 1603
H100 1.0"
CLT 1800
CBX 1800

Configuration C2

CBX 1800
CLT 1800
H130 0.75"
ELTM 1603
H100 0.75"
CLT 1800
CBX 1800

Configuration D2

CBX 1800
CLT 1800
H100 1.0"
ELTM 1603
H130 0.5"
CLT 1800
CBX 1800

Configuration B3

CBX 1800
CLT 1800
ELTM 1603
H100 1.0"
CLT 1800
CBX 1800

Configuration C3

CBX 1800
CLT 1800
H160 0.75”
ELTM 1603
H100 0.75"
CLT 1800
CBX 1800

Configuration D3

CBX 1800
CLT 1800
H100 1.0”
ELTM 1603
H160 0.5"
CLT 1800
CBX 1800

Configuration D4

CBX 1800
CLT 1800
M100 1.0”
ELTM 1603
H100 0.5”
CBX 1800
CBX 1800

The average penetration depth of the impactor in panels that achieved failure criteria was 2.10 inches with a standard mean deviation of 0.15 inches. The average panel thickness is 1.68 inches. The range of Energy to cause the failures was from 981 Joules to 1084 Joules, with an average energy of 1046 Joules.

** For additional information see tables 1 and 2 on page IV.

CONCLUSIONS & RECOMMENDATIONS

- The A Base Panels performed best when impacted with the 0.625 inch Impactor.
- The B Base Panels performed best when impacted with the 2 inch Impactor.
- In Either case the top skins of the test samples showed cracking and signs of wrinkling with top skin separation from the underlying core material as shown in Fig 14 and 15.
- Future testing will utilize panels with the total planar supported dimension that is at least 10 times the diameter of the Impactor.
- Energies required to produce failure with the 2 inch Impactor were approximately 6 times greater than the .0625 inch Impactor.
- In both the .625 inch and 2 inch testing series, the higher density cores required higher energy than the lower density cores.

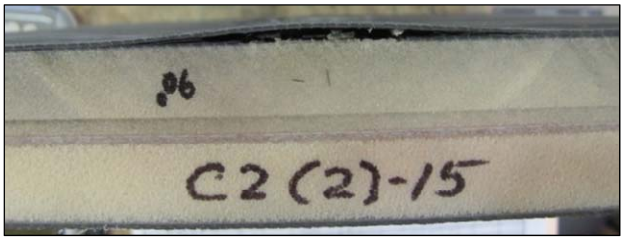


Fig 14. Edge view showing top skin separation

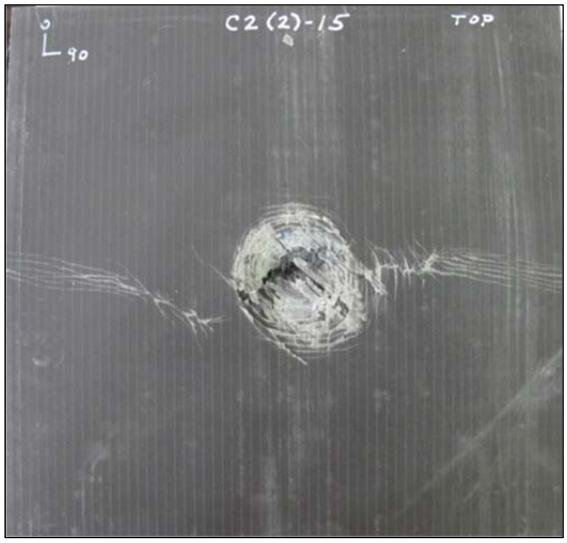


Fig 15. Same sample showing top view cracks extending to edges

Recommendations:

Continue testing with larger panel width and length dimensions in order to accommodate the 10 times diameter guideline. This may limit any edge effects that may occur during testing and thus in theory reduce the amount of top skin wrinkling.

REFERENCES

ASTM Standard D7136/D7136M *Standard Test Method for Measuring the Damage Resistance of a Fiber-Reinforced Polymer Matrix Composite to a Drop Weight Impact Event*

HDC Drawing 0632-100-100: *Impact Testing Apparatus*, sheet 1-4, p22-p25

HDC Drawing 0632-100-101SK: *Impact Test apparatus Un-instrumented impactor*, sheet 1 of 1, p28

HDC Drawing 0632-100-102: *Impact Testing Apparatus Coupon Support Base*, sheet 1 of 1, p26

HDC Drawing 0632-100-105SK: *Impact Testing Apparatus Depth Measuring Target ring*, sheet 1 of 1, p27

HDC Drawing 0632-100-107SK: *Impact Testing Apparatus Un-instrumented impactor Variations*, sheet 1 of 1, p 29

HDC Drawing 0632-100-108SK: *Impact Testing Apparatus 3 in Un-instrumented impactor*, sheet 1 of 1, p30

HDC Drawing 0632-100-109: *Impact Test Apparatus Harken Winch Installation*, sheet 1 of 1, p31

HDC Form 10.03.1 *ONR Impact Testing Report, Fig* 3, p6

HDC Form 10.03.2 *ONR Impact Test Data Collection Report*, p32

HDC Form 10.03.3 *ONR Test Sample Transfer Tracking*, p33

APPENDICES:

Table of contents

A- HDC Impact Testing Standards and Procedures. p. 23

B- Impact Velocity Calibration Curve. p. 25

C- Laminate Schedule for Test Panel Configurations. p. 26

D- Drawing 0632-100-100, sheet 1 p. 27

E- Drawing 0632-100-100, sheet 2 p. 28

F- Drawing 0632-100-100, sheet 3 p. 29

G- Drawing 0632-100-100, sheet 4 p. 30

H- Drawing 0632-100-102, sheet 1 p. 31

I- Drawing 0632-100-105SK, sheet 1 p. 32

J-Drawing 0632-100-101SK, sheet 1 p. 33

K-Drawing 0632-100-107SK, sheet 1 p. 34

L-Drawing 0632-100-108SH, sheet 1 p. 35

M-Drawing 0632-100-109, sheet 1, p. 36

N-Data Sheets for Infusing Composite Structures p. 37

Appendix A

Impact Test Procedure:

Samples to be Tested were Identified at least 24 hrs prior to testing.

1. Test samples are prepared In accordance with paragraph 6 of this standard.
2. Test samples were grouped in stacks and identified by group number.
3. Mark Face, reverse and side with Group stamp and specimen ID.

a. Face and Reverse marked with white out marker.
b. Side marked with black marker.

4. Pre maintenance checks and services were conducted to Impact Testing apparatus, As a minimum:

a. Check Impact Testing frame and hardware for cracked or missing supports, loose or missing bolts and nuts, overall trueness of parts.
b. Check function of carriage in slides.
c. Check function of release mechanism.
d. Check serviceability of 3/8 inch carriage halyard and trigger release lines.
e. Check function and serviceability of guide sheaves.
f. Check levelness of coupon test base.
g. Check table clamps for worn or broken parts.
h. Check table clamps for function, adjust clamping force as necessary.
i. Install impactor into impactor adapter using a layer of grease on threads to prevent galling.
j. Clean and lubricate impactor IAW paragraph 4 of this standard.
k. Attach optical gate sensor and plug in optical gate timing comp housing to 110v AC source.
l. Conduct self test of Optical gate timer.
m. Check optical gate “flag” for damage and to ensure trigger depth is adjusted properly.

5. Select Test coupons and place in localized area near Impact Testing Apparatus.
6. Remove lockout device.
7. Raise carriage at least 2 feet and lock out to prevent accidental dropping.
8. Place sample coupon into test position assuring the 0 axis is aligned with the fore and aft direction on support base until the forward surface contacts the support base guide pins, Engage table clamps to hold sample securely.
9. Remove lockout and raise carriage to test drop height.
10. Secure raising line and release line in cam cleats.
11. Announce in a loud voice “CLEAR” look and listen for any interference in the path of the drop carriage, impactor, Impact point and listen for any response alerting that the drop test must be halted. If no responses continue with step 13.
12. Pull the trigger lanyard and observe the drop carriage travel and impact.

13. After impact take a photo graph of the impactor sample interface and insure the second strike prevention stop mechanism has deployed and is working. Depending on rebound height the impactor may not have rebounded clear of the test sample.
14. Inspect /measure impactor collar for top skin wrinkle and or bounce of impactor and annotate on report form.
15. Lower release crosshead and attach to impactor carriage.
16. Raise impactor carriage at least 2 feet and lock out carriage.
17. Insure kinetic indicator and full impactor ravel scale are even
18. Measure impactor full travel scale and annotate on report form
19. Release table clamps and remove test sample coupon.
20. Place Test sample coupon in measurement area and photograph both sides of panel and any damage therein, NOTE the picture numbers and record this information on HDC 10.03.2.
21. Measure the damage and mark the test sample to show damage direction and length of damage on HDC form 10.03.2 and record information in designated blocks.
22. When all samples are tested for that group or groups transcribe data to HDC Electronic form 10.03.1 after all data is transcribed endure the spreadsheet is locked.
23. Print a copy of HDC form 10.03.1 and have project manager sign a copy as a true copy.
24. Put HDC form 10.03.1 and HDC form 10.03.2 in the ONR report form binder.
25. Download all photos of the test cycle and rename photo to photo naming convention as outlined in paragraph 2 of this standard.
26. When any sample is released to outside HDC parties note in HDC form 10.03.3 and store in front of ONR report form binder.

Appendix B

Impact Velocity Calibration Curve

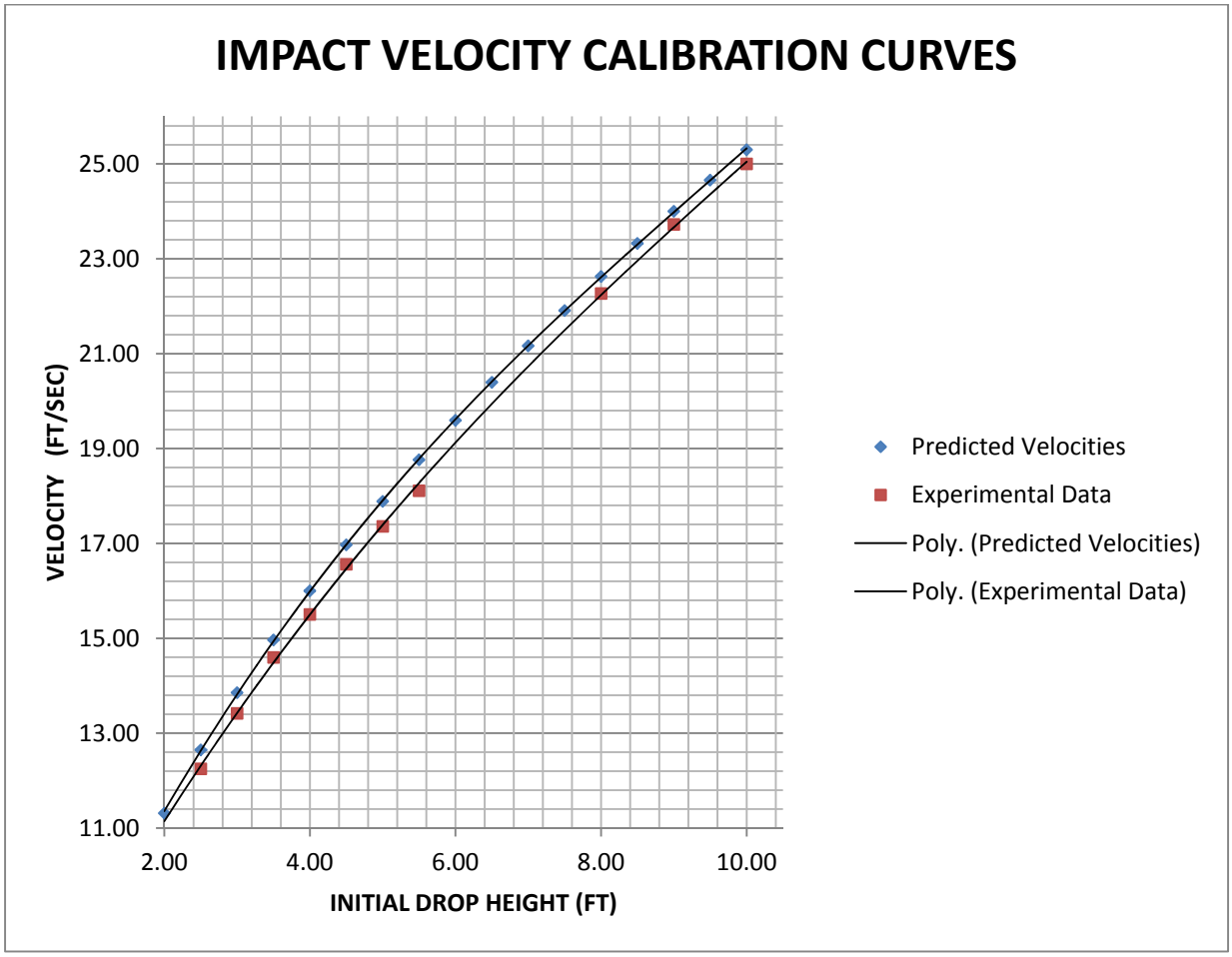


Fig16. Impact Velocity Calibration Curve

Appendix C Laminate Schedule for Test Samples

Configuration A
CBX 1800
CLT 1800
ELTM 1603
H100 1.5"
CLT 1800
CBX 1800

Configuration B
CBX 1800
CLT 1800
H100 0.5"
ELTM 1603
H100 1.0"
CLT 1800
CBX 1800

Configuration C
CBX 1800
CLT 1800
H100 0.75"
ELTM 1603
H100 0.75"
CLT 1800
CBX 1800

Configuration D
CBX 1800
CLT 1800
H100 1.0"
ELTM 1603
H100 0.5"
CLT 1800
CBX 1800

Configuration B2
CBX 1800
CLT 1800
H130 0.5"
ELTM 1603
H100 1.0"
CLT 1800
CBX 1800

Configuration C2
CBX 1800
CLT 1800
H130 0.75"
ELTM 1603
H100 0.75"
CLT 1800
CBX 1800

Configuration D2
CBX 1800
CLT 1800
H100 1.0"
ELTM 1603
H130 0.5"
CLT 1800
CBX 1800

Configuration B3
CBX 1800
CLT 1800
H160 0.5"
ELTM 1603
H100 1.0"
CLT 1800
CBX 1800

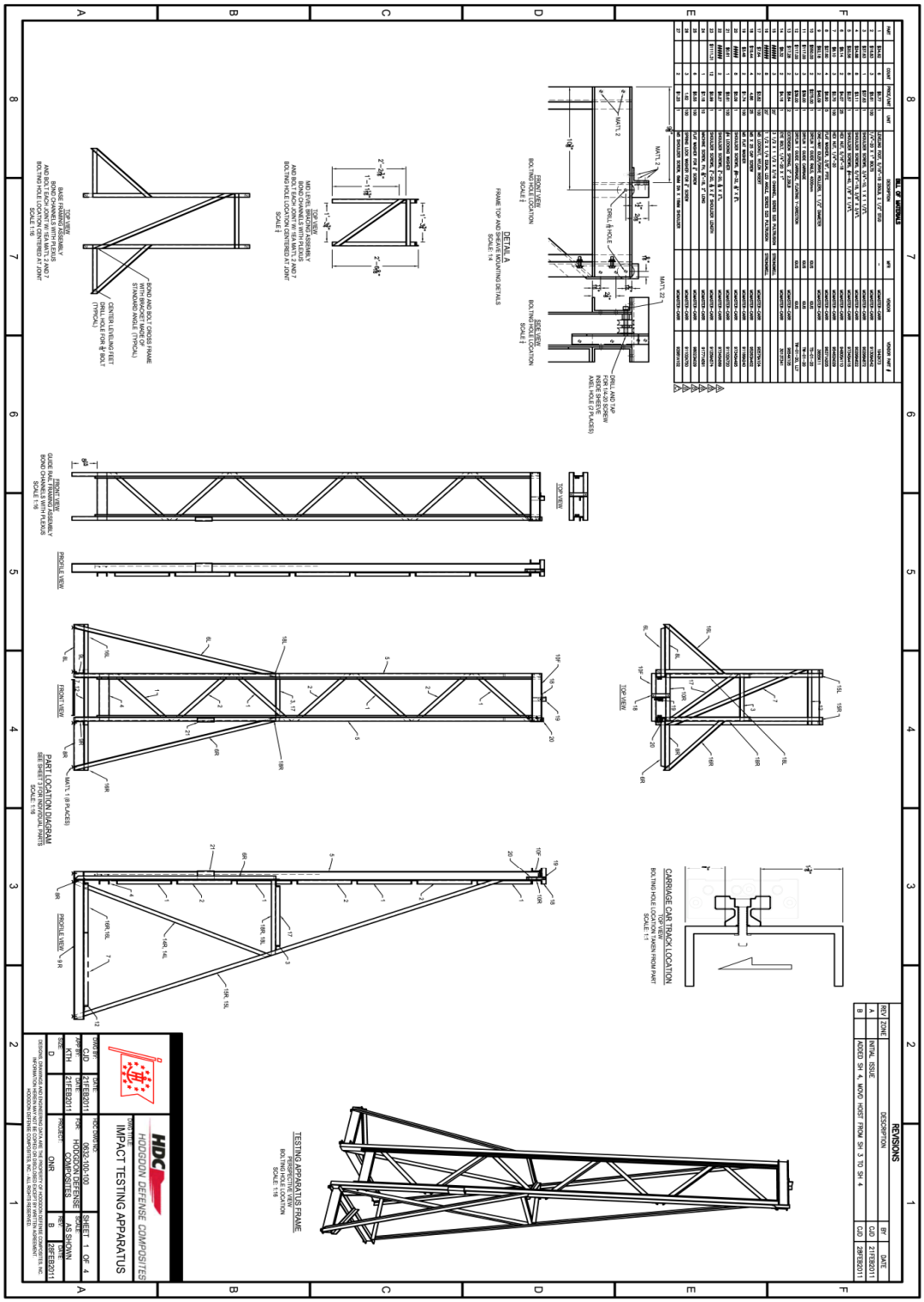
Configuration C3
CBX 1800
CLT 1800
H160 0.75"
ELTM 1603
H100 0.75"
CLT 1800
CBX 1800

Configuration D3
CBX 1800
CLT 1800
H100 1.0"
ELTM 1603
H160 0.5"
CLT 1800
CBX 1800

Configuration D4
CBX 1800
CLT 1800
M100 1.0"
ELTM 1603
H100 0.5"

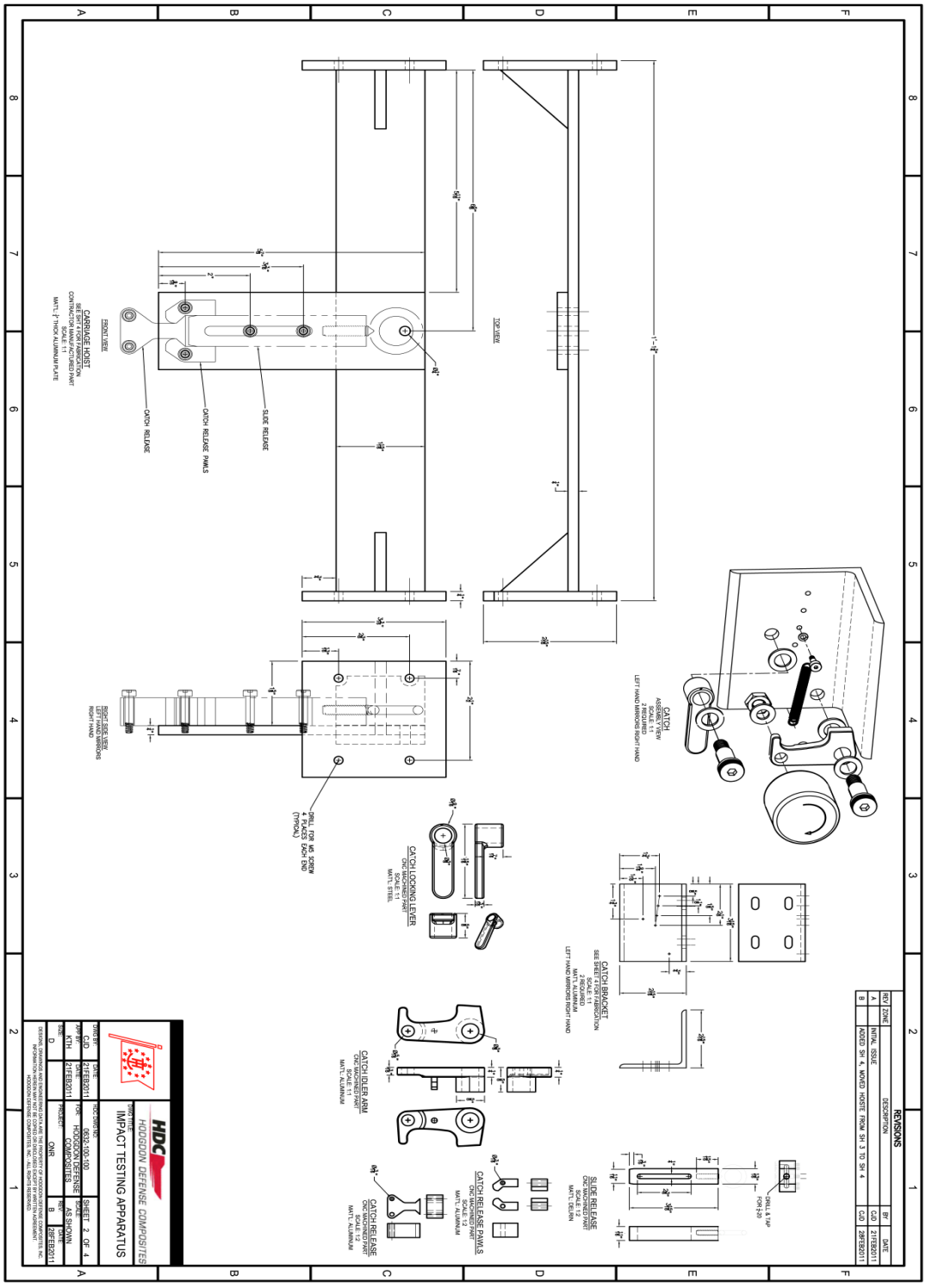
Table 3. Laminate Configurations

Appendix D



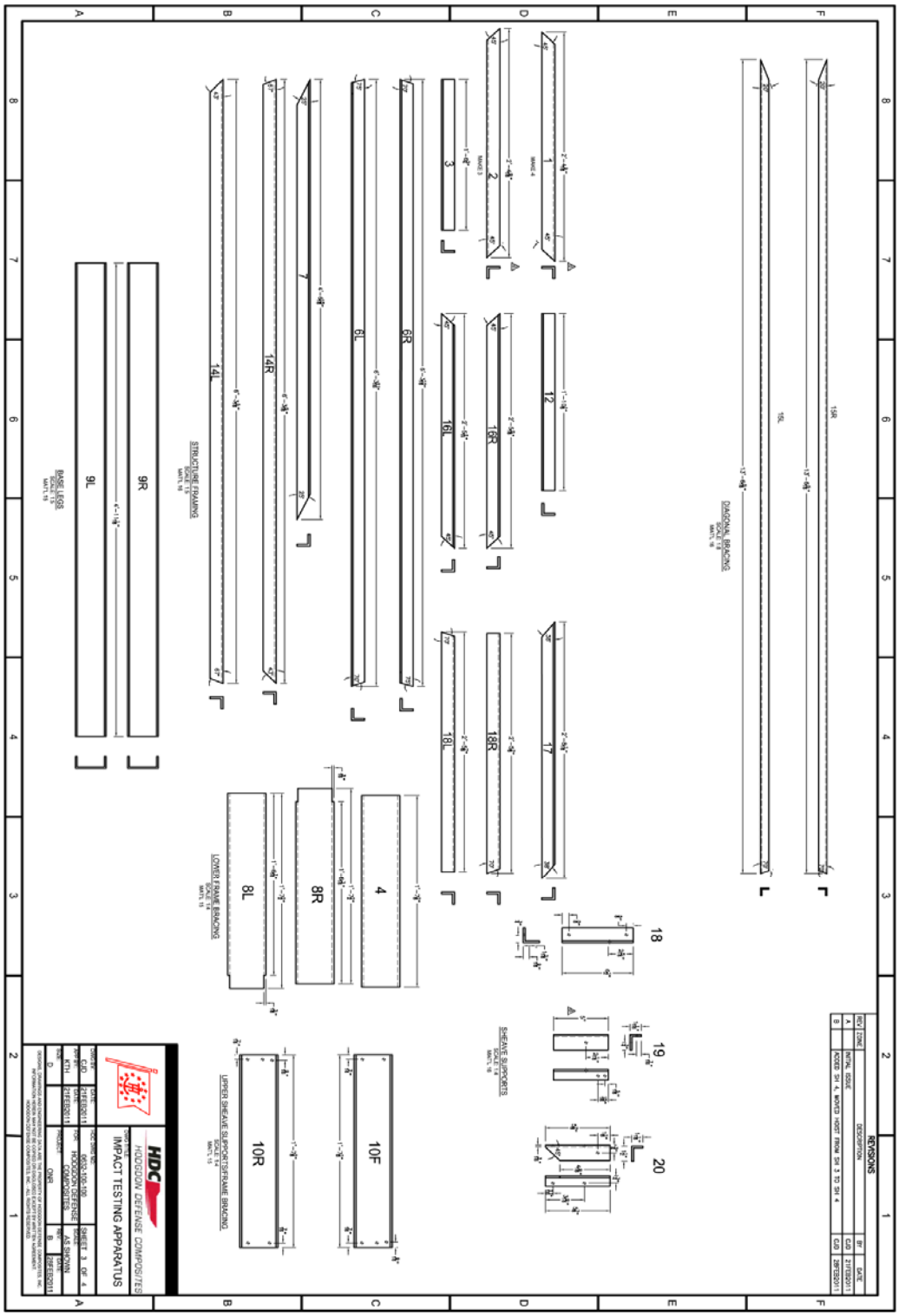
Drawing 0632-100-100 sheet 1 of 4

Appendix E



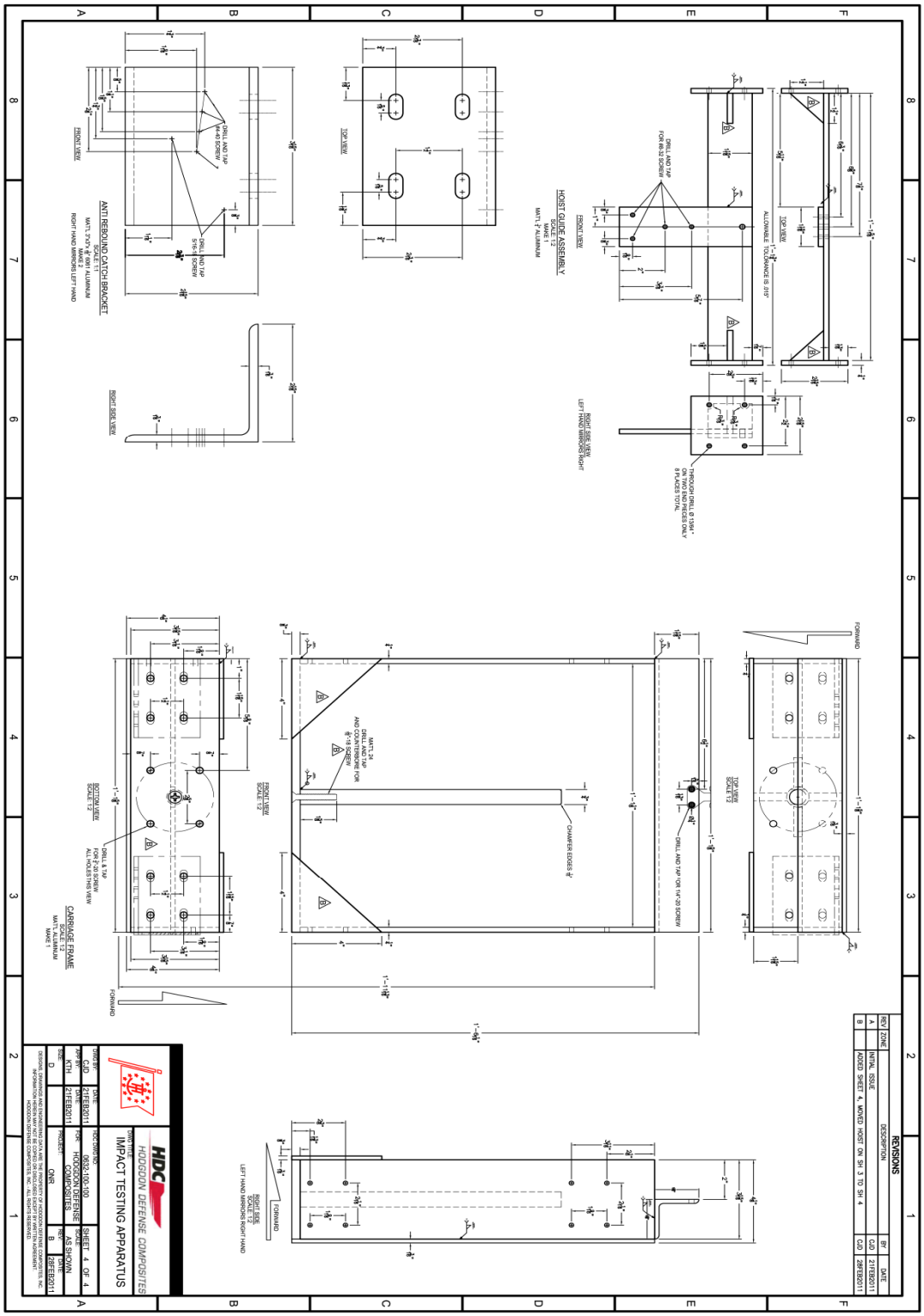
Drawing 0632-100-100 sheet 2 of 4

Appendix F



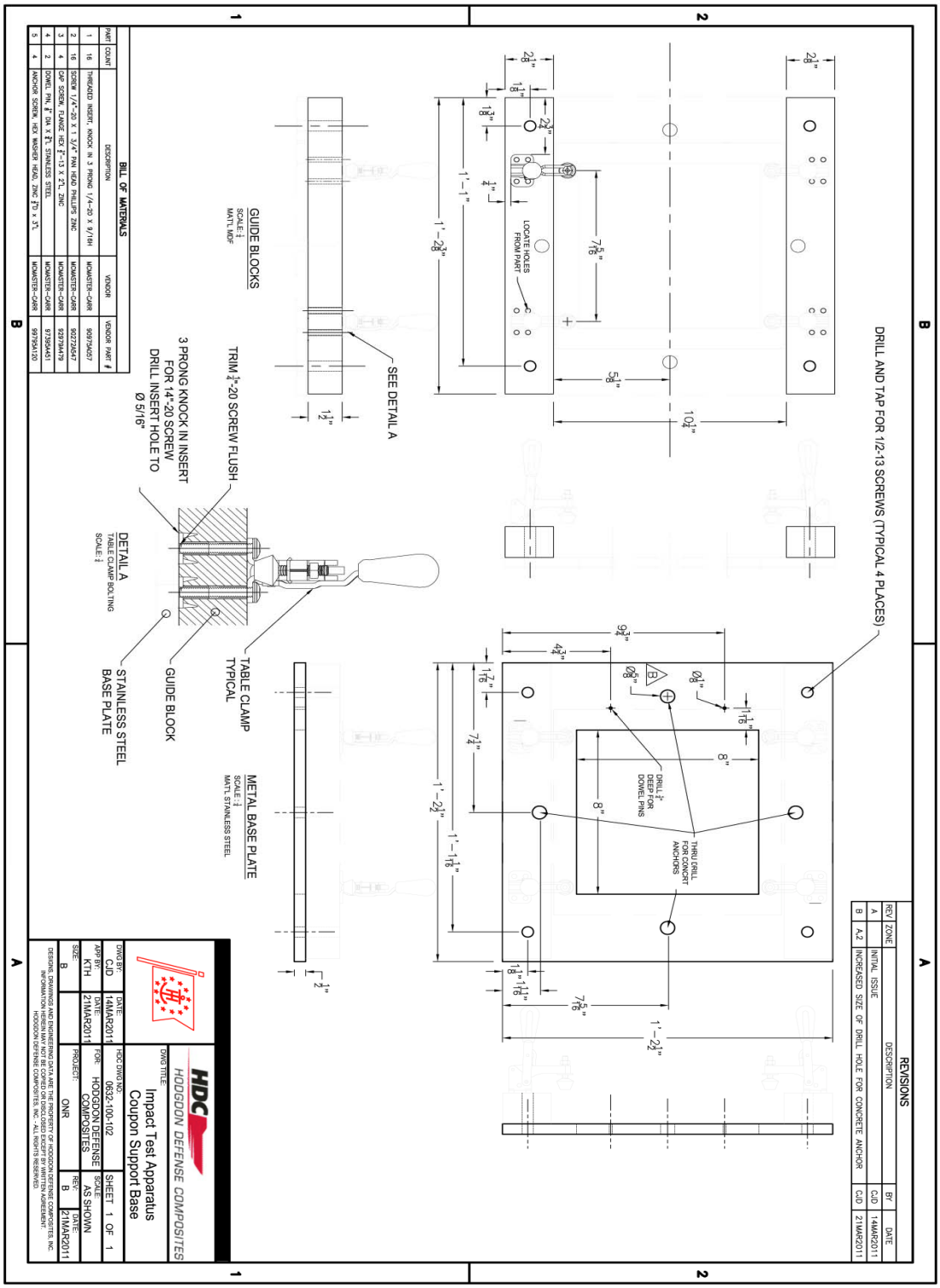
Drawing 0632-100-100 sheet 3 of 4

Appendix G



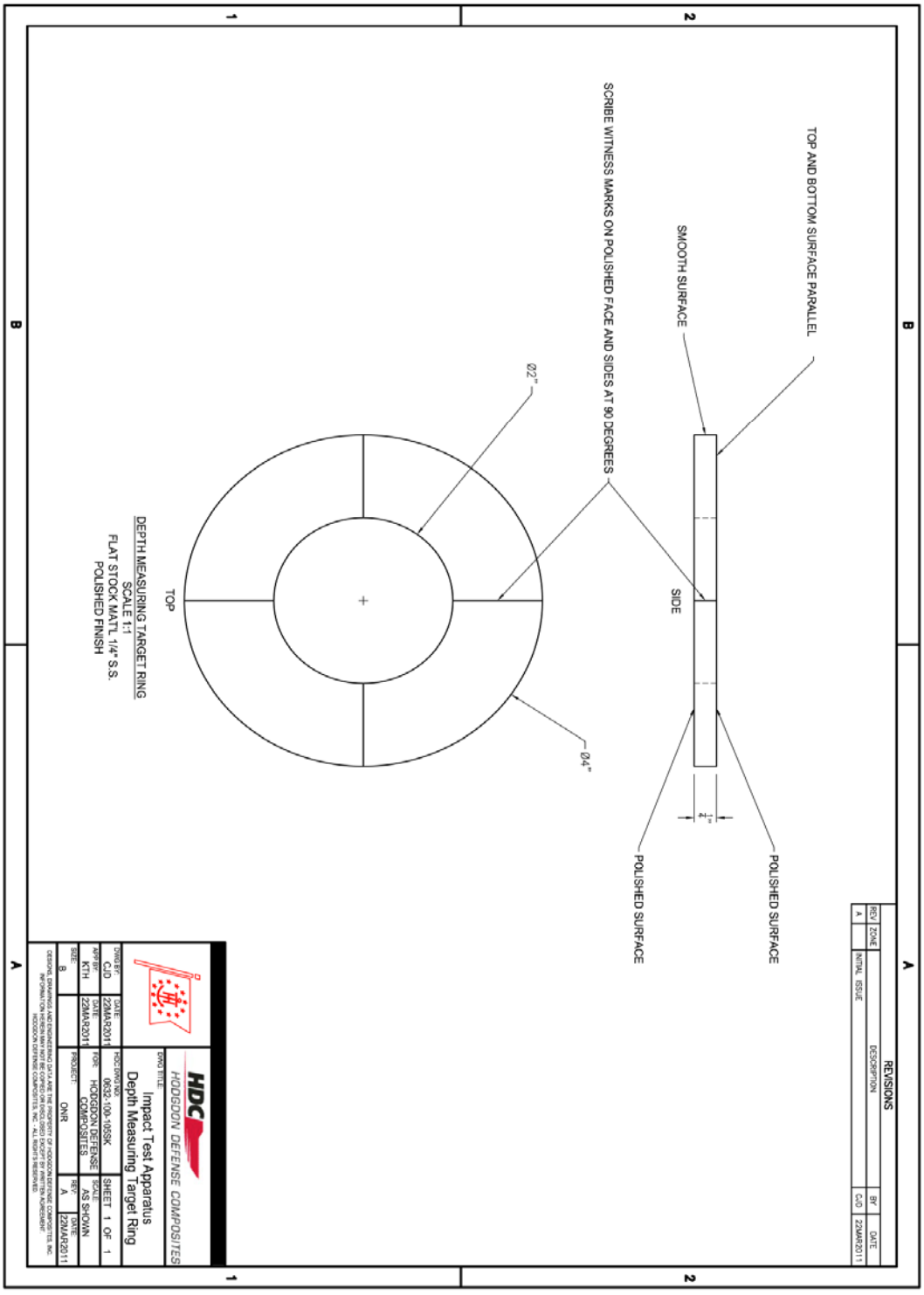
Drawing 0632-100-100 sheet 4 of 4

Appendix H



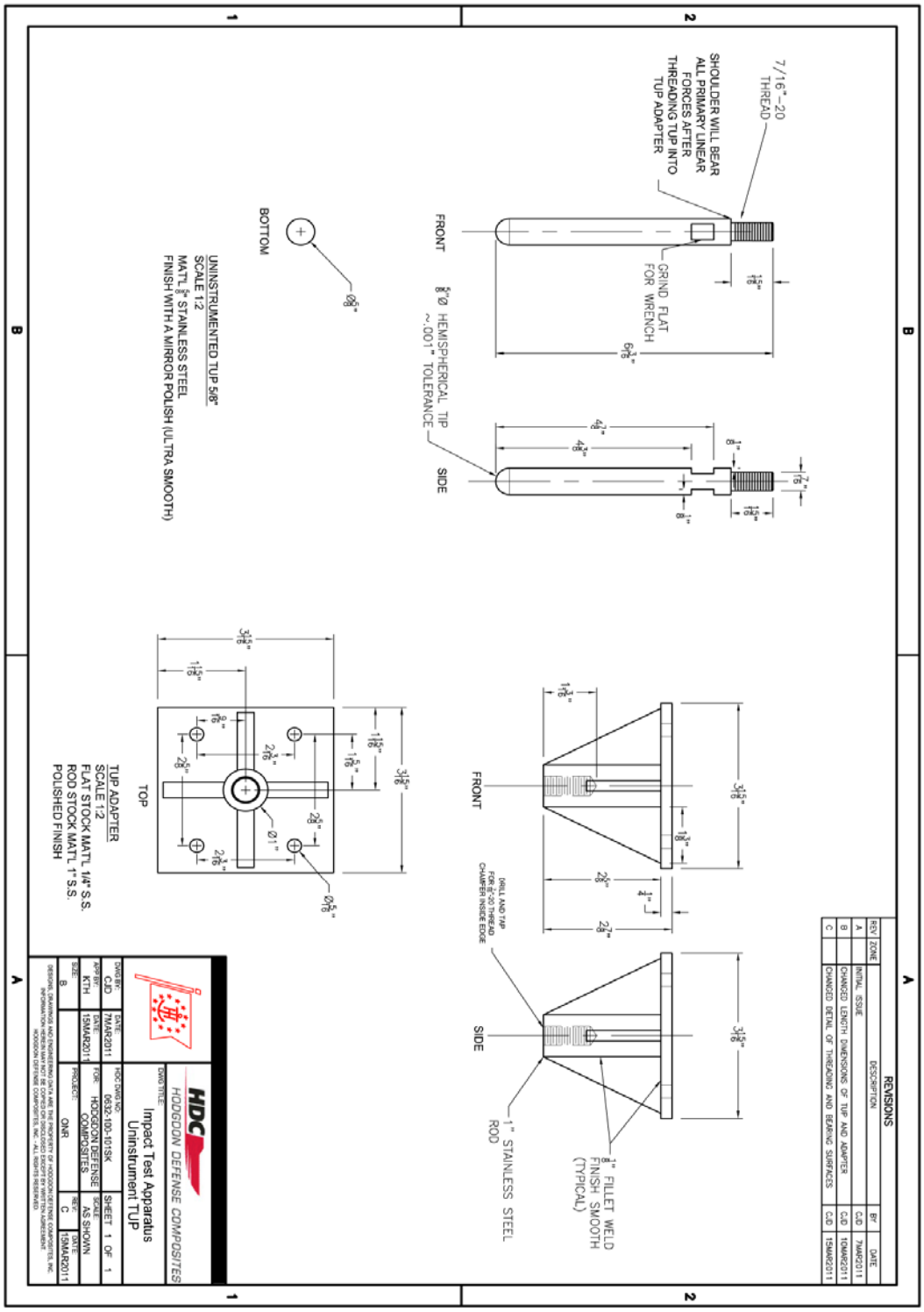
Drawing 0632-100-102 sheet 1 of 1

Appendix I



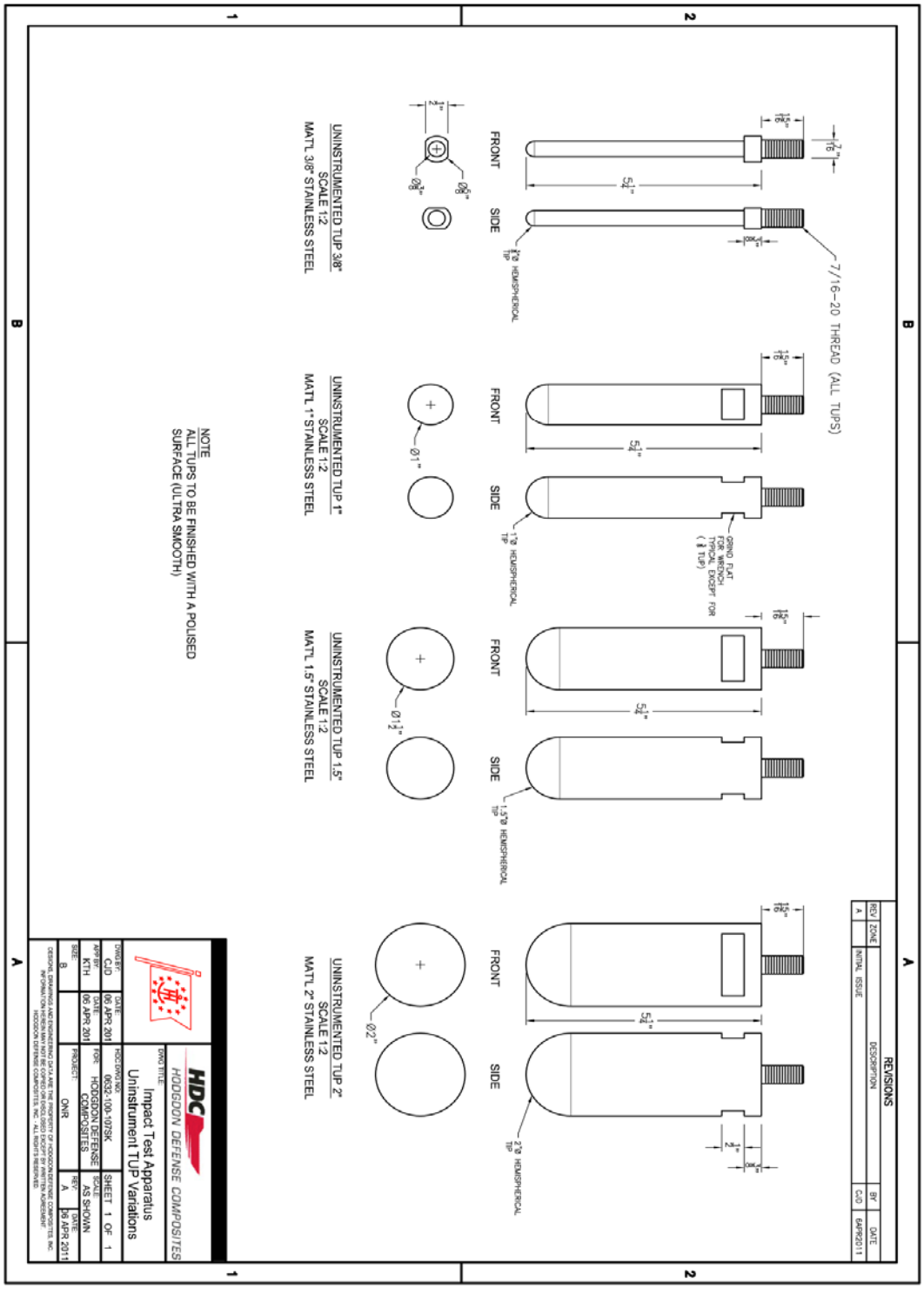
Drawing 0632-100-105SK sheet 1of 1

Appendix J



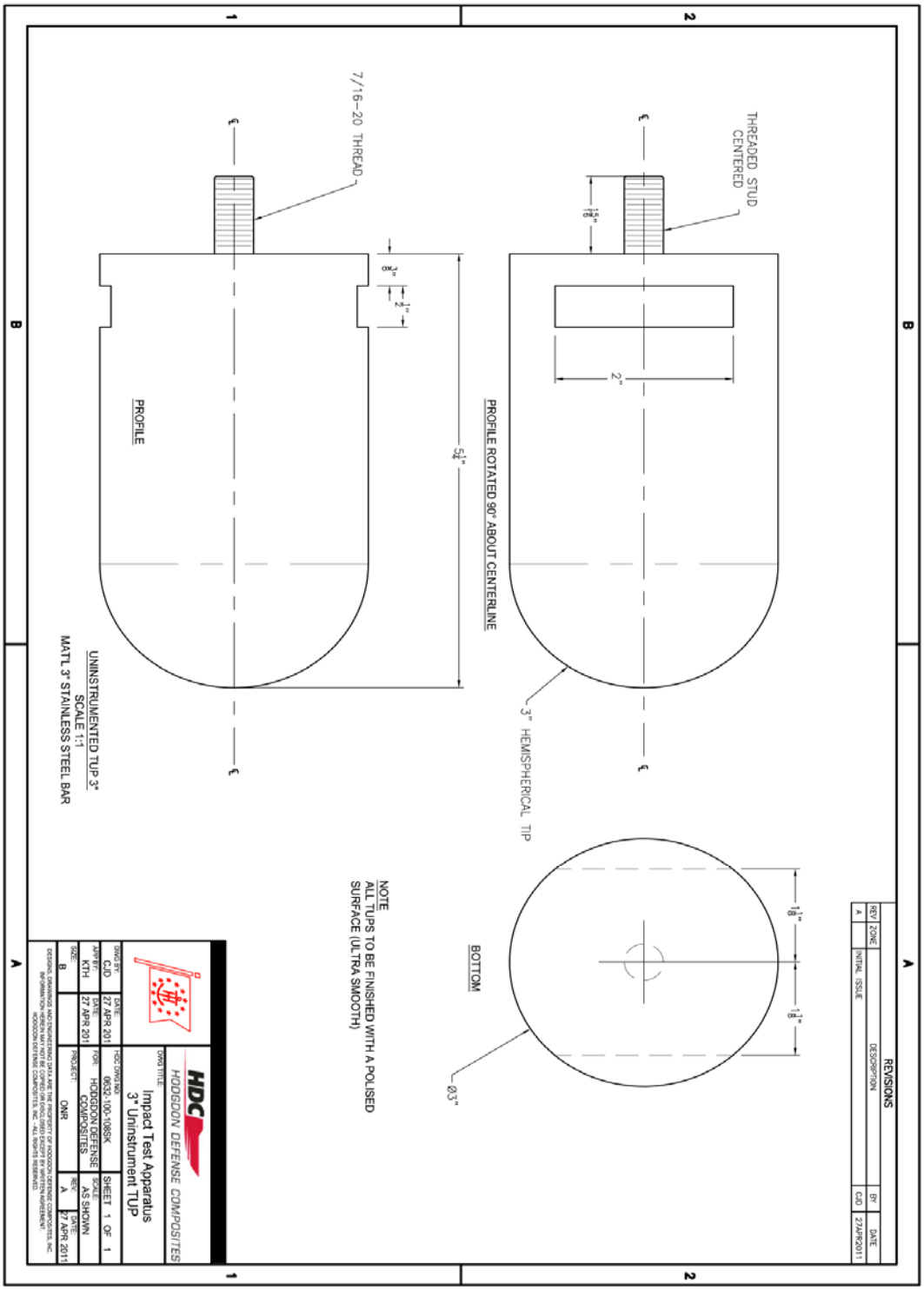
Drawing 0632-100-101SK sheet 1 of 1

Appendix K



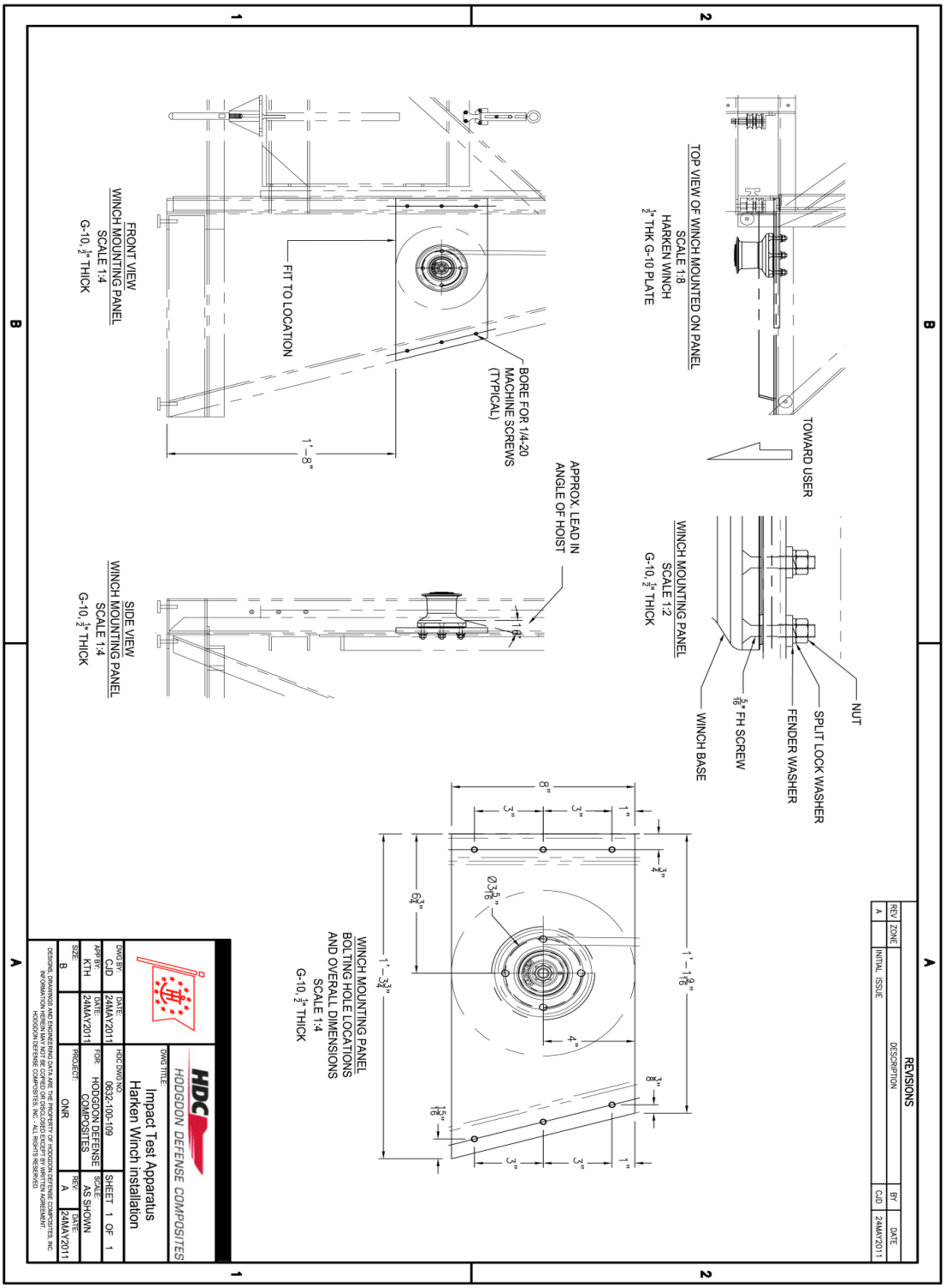
Drawing 0632-100-107SK sheet 1 of 1

Appendix L



Drawing 0632-100-108SK sheet 1 of 1

Appendix M



Drawing 0632-100-109 sheet 1 of 1

Appendix N

Data Sheets for Infusing Composite Structures

Project Number: ***0632***

Part Number: ***Config B2(3)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 02/11/2011 **Shop Temperature:** 67.5 °F

Name(s): Jason Wight **Humidity:** 61 %RH

Start: 8:50 **AM** / PM Vacuum Level: 29.5 "of Hg

Stop: 9:10 **AM** / PM Vacuum Level: 29.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config B2(3)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 02/11/2011 **Shop Temperature:** 69.1 °F

Name(s): Jason Wight **Humidity:** 60 %RH

Infusion: Resin: 79 °F

Start: 9:44 **AM** / PM Temp: 68 °F Vacuum Level: 29.5 "of Hg

Stop: 10:05 **AM** / PM Temp: 75 °F Vacuum Level: 29.5 "of Hg

Comments: Infused in 21 minutes

Project Number: ***0632***

Part Number: ***Config B3(1)***

Data Sheet for Infusing Composite Structures

Date: 02/08/2011 **Shop Temperature:** 73.3 °F

Name(s): Jason Wight **Humidity:** 34 %RH

Sara Boston

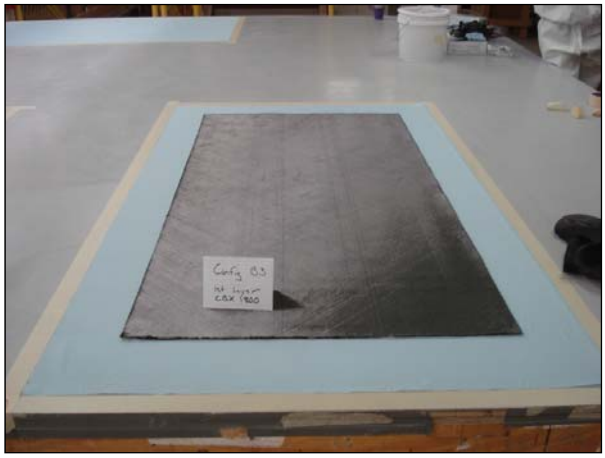
LAY-UP EXAMINATION

Panel Lay-Up:

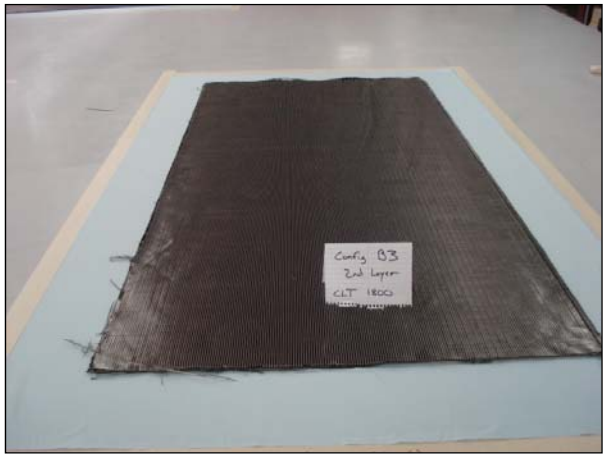
Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H160 (0.5”)			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (1.0”)			√
8		CLT 1800			√
9		CBX 1800			√



1st Layer – CBX 1800



2nd Layer – CLT 1800

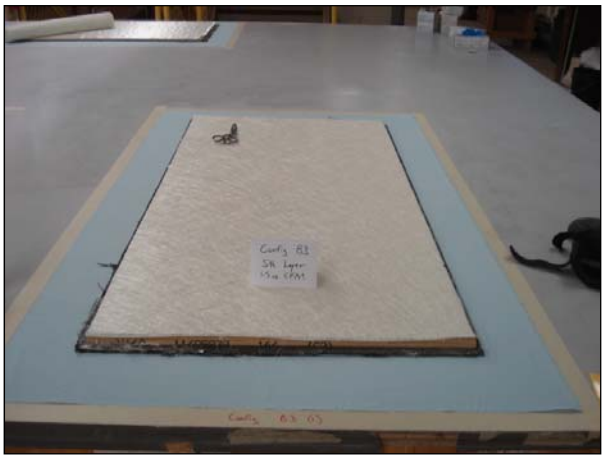
y



3rd Layer – H160 (0.5”) Core



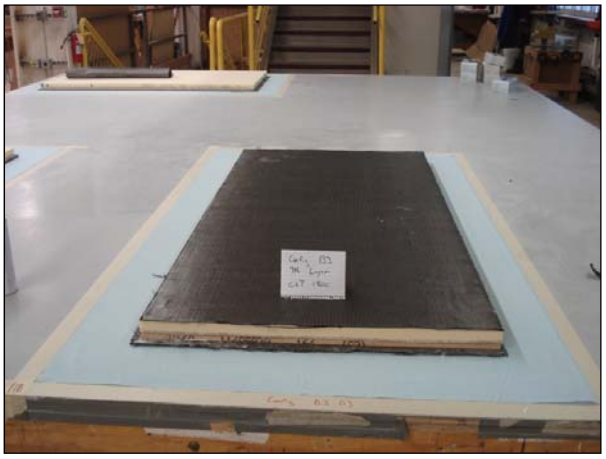
4th Layer – ELTM 1603



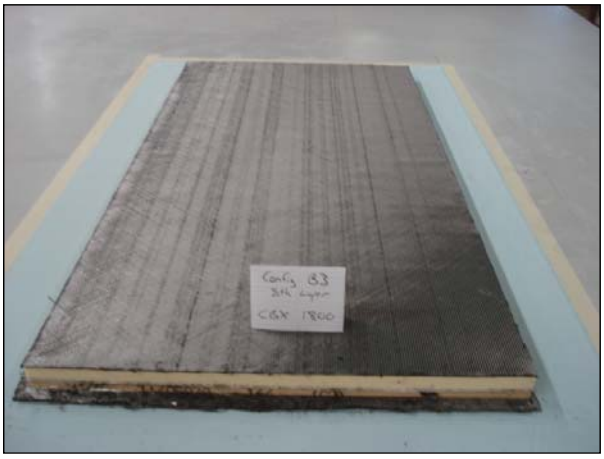
5th Layer – 1.5oz CFM



6th Layer – H100 (1.0”) Core



7th Layer – CLT 1800



8th Layer – CBX 1800

Project Number: ***0632***

Part Number: ***Config B3(1)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 02/08/2011 **Shop Temperature:** 73 °F

Name(s): Jason Wight **Humidity:** 34 %RH

Sara Boston

Start: 2:45 AM / **PM** Vacuum Level: 30 "of Hg

Stop: 3:00 AM / **PM** Vacuum Level: 30 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config B3(1)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 02/08/2011 **Shop Temperature:** 73 °F

Name(s): Jason Wight **Humidity:** 34 %RH

Sara Boston

Infusion: Resin: 79 °F

Start: 3:12 AM / **PM** Temp: 73 °F Vacuum Level: 30 "of Hg

Stop: 3:37 AM / **PM** Temp: 78 °F Vacuum Level: 30 "of Hg

Comments: Infused in 25 minutes

Project Number: ***0632***

Part Number: ***Config B3(2)***

Data Sheet for Infusing Composite Structures

Date: 02/08/2011 **Shop Temperature:** 73.4 °F

Name(s): Jason Wight **Humidity:** 33 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H160 (0.5”)			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (1.0”)			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config B3(2)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 02/09/2011 **Shop Temperature:** 64 °F

Name(s): Jason Wight **Humidity:** 49 %RH

Sara Boston

Start: 7:01 **AM** / PM Vacuum Level: 28.5 "of Hg

Stop: 7:16 **AM** / PM Vacuum Level: 28.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config B3(2)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 02/08/2011 **Shop Temperature:** 67 °F

Name(s): Jason Wight **Humidity:** 49 %RH

Sara Boston

Infusion: Resin: 95 °F

Start: 8:43 **AM** / PM Temp: 67 °F Vacuum Level: 28.5 "of Hg

Stop: 8:55 **AM** / PM Temp: 86 °F Vacuum Level: 28.5 "of Hg

Comments: Infused in 12 minutes

Project Number: ***0632***

Part Number: ***Config B3(3)***

Data Sheet for Infusing Composite Structures

Date: 02/08/2011 **Shop Temperature:** 73.4 °F

Name(s): Jason Wight **Humidity:** 33 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H160 (0.5”)			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (1.0”)			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

1 Part Number: Config B3(3)

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 02/08/2011 **Shop Temperature:** 73.4 °F

Name(s): Jason Wight **Humidity:** 34 %RH

Sara Boston

Start: 2:45 AM / **PM** Vacuum Level: 27.5 "of Hg

Stop: 3:00 AM / **PM** Vacuum Level: 27.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config B3(3)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 02/08/2011 **Shop Temperature:** 73 °F

Name(s): Jason Wight **Humidity:** 34 %RH

Sara Boston

Infusion: Resin: 87 °F

Start: 3:40 AM / **PM** Temp: 74.5 °F Vacuum Level: 27.5 “of Hg

Stop: 4:00 AM / **PM** Temp: 81 °F Vacuum Level: 27.5 “of Hg

Comments: Infused in 20 minutes

Project Number: ***0632***

Part Number: ***Config B(1)***

Data Sheet for Infusing Composite Structures

Date: 01/25/2011 **Shop Temperature:** 71.1 °F

Name(s): Jason Wight **Humidity:** 21 %RH

Sara Boston

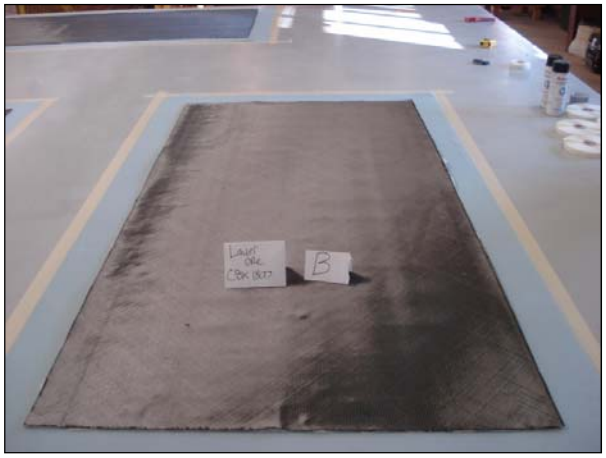
LAY-UP EXAMINATION

Panel Lay-Up:

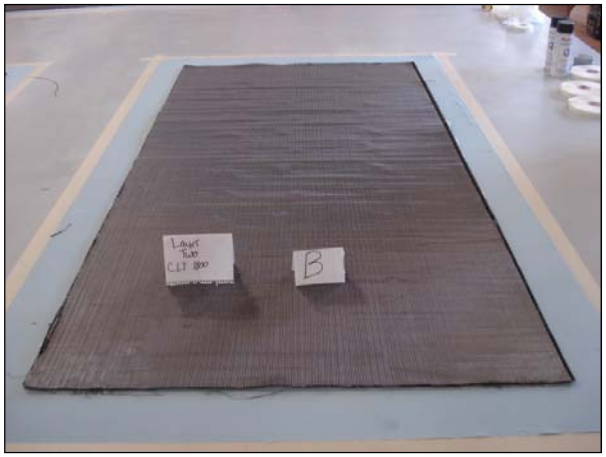
Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H100 (0.5”)			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (1.0”)			√
8		CLT 1800			√
9		CBX 1800			√



1st Layer – CBX 1800



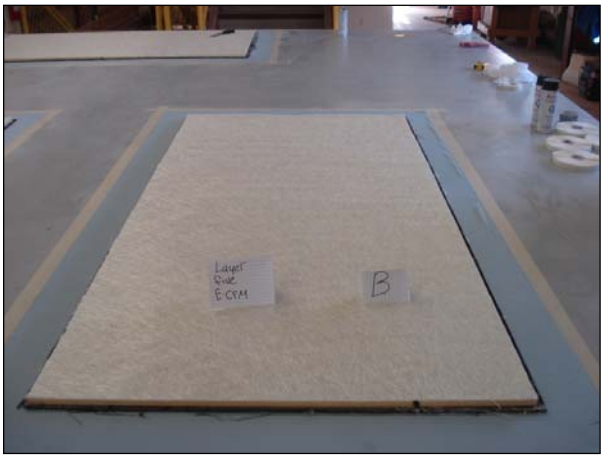
2nd Layer – CLT 1800



3rd Layer – H100 (0.5”) Core



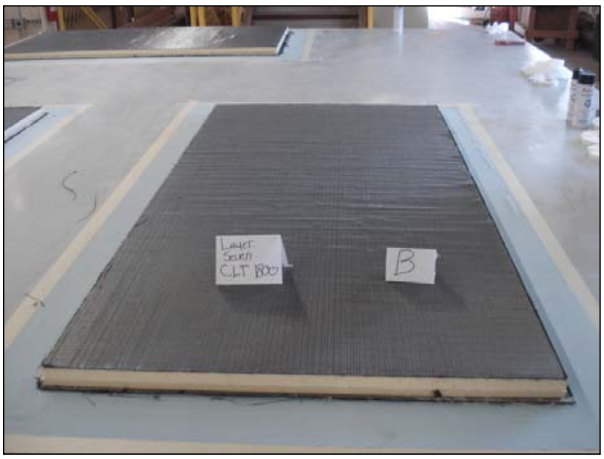
4th Layer – E LTM 1603



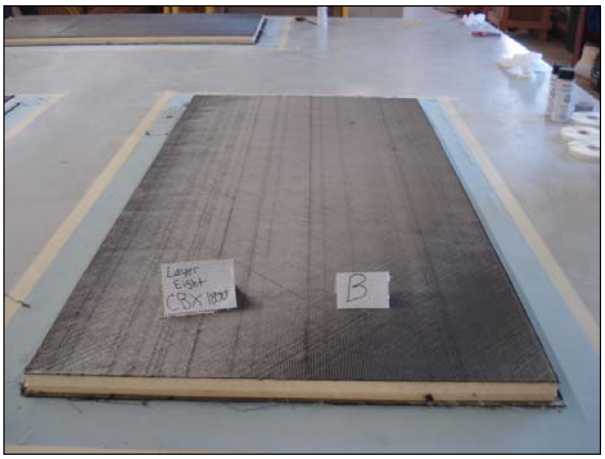
5th Layer – 1.5oz CFM



6th Layer – H100 (1.0”) Core



7th Layer – CLT 1800



8th Layer – CBX 1800

Project Number: ***0632***

Part Number: ***Config B(1)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 01/25/2011 **Shop Temperature:** 71.1 °F

Name(s): Jason Wight **Humidity:** 21 %RH

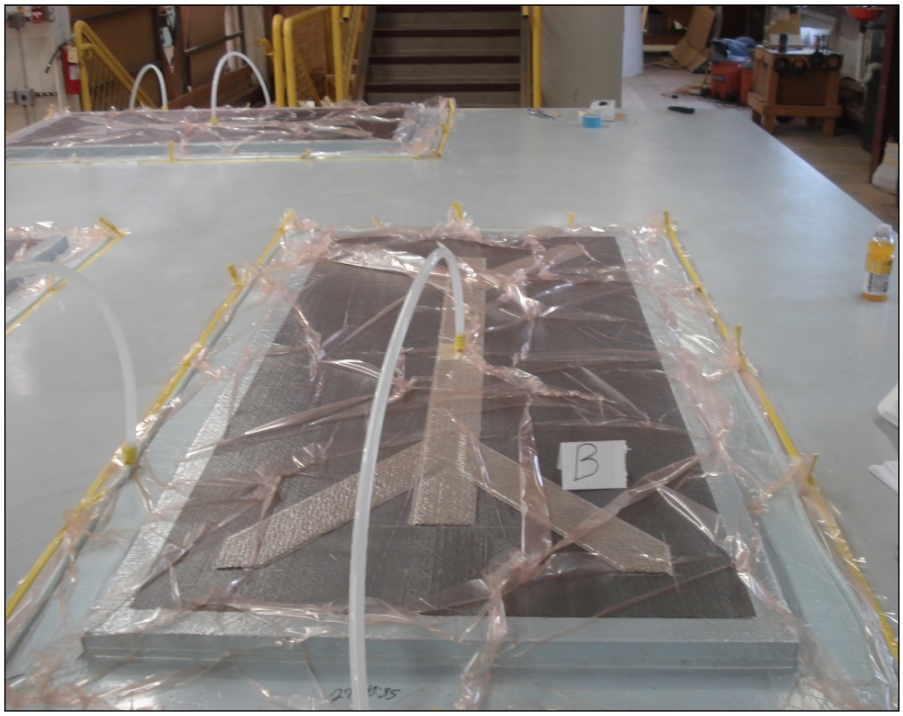
Sara Boston

Start: 11:15 AM / **PM** Vacuum Level: 27 "of Hg

Stop: 11:30 AM / **PM** Vacuum Level: 27 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



Project Number: ***0632***

Part Number: ***Config B(1)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 01/25/2011 **Shop Temperature:** 71.1 °F

Name(s): Jason Wight **Humidity:** 21 %RH

Sara Boston

Infusion: Resin: 78.3 °F

Start: 12:35 AM / **PM** Temp: 72.5 °F Vacuum Level: 27 "of Hg

Stop: 12:53 AM / **PM** Temp: 78.2 °F Vacuum Level: 27 "of Hg

Comments: Infused in 18 minutes

Project Number: ***0632***

Part Number: ***Config B(2)***

Data Sheet for Infusing Composite Structures

Date: 01/25/2011 **Shop Temperature:** 71.3 °F

Name(s): Jason Wight **Humidity:** 21 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H100 (0.5”)			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (1.0”)			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config B(2)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 01/25/2011 **Shop Temperature:** 71.1 °F

Name(s): Jason Wight **Humidity:** 33 %RH

Sara Boston

Start: 11:00 **AM** / PM Vacuum Level: 30 "of Hg

Stop: 11:15 **AM** / PM Vacuum Level: 29.75 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config B(2)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 01/25/2011 **Shop Temperature:** 71.3 °F

Name(s): Jason Wight **Humidity:** 21 %RH

Sara Boston

Infusion: Resin: 80 °F

Start: 1:00 AM / **PM** Temp: 70.7 °F Vacuum Level: 30 "of Hg

Stop: 1:17 AM / **PM** Temp: 80.9 °F Vacuum Level: 30 "of Hg

Comments: Infused in 17 minutes

Project Number: ***0632***

Part Number: ***Config B(3)***

Data Sheet for Infusing Composite Structures

Date: 01/25/2011 **Shop Temperature:** 71.3 °F

Name(s): Jason Wight **Humidity:** 21 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H100 (0.5”)			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (1.0”)			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config B(3)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 01/25/2011 **Shop Temperature:** 71.1 °F

Name(s): Jason Wight **Humidity:** 33 %RH

Sara Boston

Start: 11:00 **AM** / PM Vacuum Level: 28.5 "of Hg

Stop: 11:15 **AM** / PM Vacuum Level: 28.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config B(3)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 01/25/2011 **Shop Temperature:** 71.3 °F

Name(s): Jason Wight **Humidity:** 21 %RH

Sara Boston

Infusion: Resin: 80.7 °F

Start: 1:21 AM / **PM** Temp: 71.4 °F Vacuum Level: 28.5 “of Hg

Stop: 1:40 AM / **PM** Temp: 80.3 °F Vacuum Level: 28.5 “of Hg

Comments: Infused in 19 minutes

Project Number: ***0632***

Part Number: ***Config C2(1)***

Data Sheet for Infusing Composite Structures

Date: 02/23/2011 **Shop Temperature:** 72 °F

Name(s): Jason Wight **Humidity:** 51 %RH

Sara Boston

LAY-UP EXAMINATION

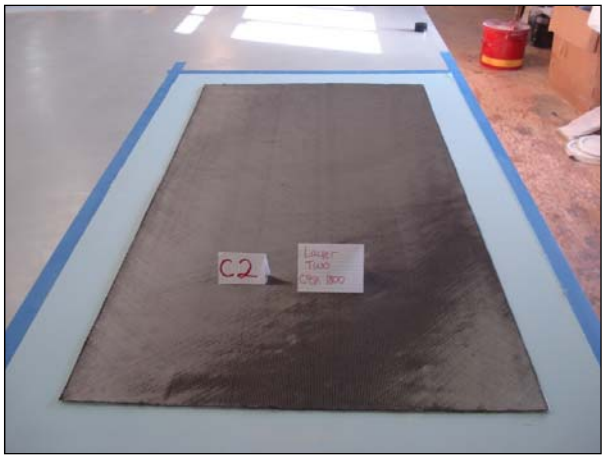
Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

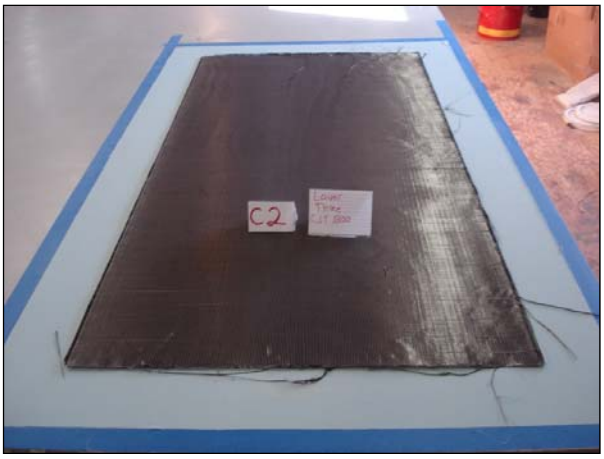
Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H130 (0.75")			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (0.75")			√
8		CLT 1800			√
9		CBX 1800			√

Picture Not Available



1st Layer – E-Veil

2nd Layer – CBX 1800





3rd Layer – CLT 1800

4th Layer – H130 (0.75") Core



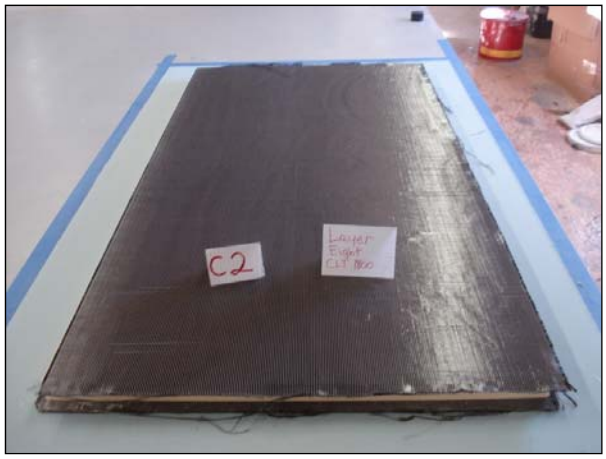
5th Layer – ELTM 1603



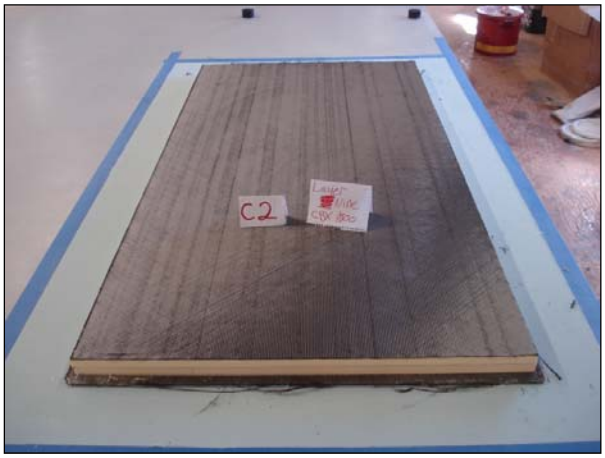
6th Layer – 1.5oz CFM



7th Layer – H100 (0.75”) Core



8th Layer – CLT 1800



9th Layer – CBX 1800

Project Number: ***0632***

Part Number: ***Config C2(1)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 02/23/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 54 %RH

Sara Boston

Start: 11:10 **AM** / PM Vacuum Level: 29.5 "of Hg

Stop: 11:25 **AM** / PM Vacuum Level: 29.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config C2(1)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 02/23/2011 **Shop Temperature:** 73 °F

Name(s): Jason Wight **Humidity:** 51 %RH

Sara Boston

Infusion: Resin: 82 °F

Start: 12:38 AM / **PM** Temp: 72 °F Vacuum Level: 29.5 "of Hg

Stop: 12:56 AM / **PM** Temp: 83 °F Vacuum Level: 29.5 "of Hg

Comments: Infused in 18 minutes

Project Number: ***0632***

Part Number: ***Config C2(2)***

Data Sheet for Infusing Composite Structures

Date: 02/23/2011 **Shop Temperature:** 72 °F

Name(s): Jason Wight **Humidity:** 54 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H130 (0.75”)			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (0.75”)			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config C2(2)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 02/23/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 56 %RH

Sara Boston

Start: 11:10 **AM** / PM Vacuum Level: 27 "of Hg

Stop: 11:25 **AM** / PM Vacuum Level: 26.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config C2(2)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 02/23/2011 **Shop Temperature:** 73 °F

Name(s): Jason Wight **Humidity:** 52 %RH

Sara Boston

Infusion: Resin: 91 °F

Start: 1:13 AM / **PM** Temp: 73 °F Vacuum Level: 27 "of Hg

Stop: 1:25 AM / **PM** Temp: 89 °F Vacuum Level: 27 "of Hg

Comments: Infused in 12 minutes

Project Number: ***0632***

Part Number: ***Config C2(3)***

Data Sheet for Infusing Composite Structures

Date: 02/23/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 56 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H130 (0.75”)			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (0.75”)			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config C2(3)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 02/23/2011 **Shop Temperature:** 72 °F

Name(s): Jason Wight **Humidity:** 54 %RH

Sara Boston

Start: 11:10 **AM** / PM Vacuum Level: 28.5 "of Hg

Stop: 11:25 **AM** / PM Vacuum Level: 28.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config C2(3)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 02/23/2011 **Shop Temperature:** 75 °F

Name(s): Jason Wight **Humidity:** 51 %RH

Sara Boston

Infusion: Resin: 107 °F

Start: 3:02 AM / **PM** Temp: 75 °F Vacuum Level: 28.5 “of Hg

Stop: 3:15 AM / **PM** Temp: 95 °F Vacuum Level: 28.5 “of Hg

Comments: Infused in 13 minutes

Project Number: ***0632***

Part Number: ***Config C3(1)***

Data Sheet for Infusing Composite Structures

Date: 03/01/2011 **Shop Temperature:** 72 °F

Name(s): Jason Wight **Humidity:** 64 %RH

Sara Boston

LAY-UP EXAMINATION

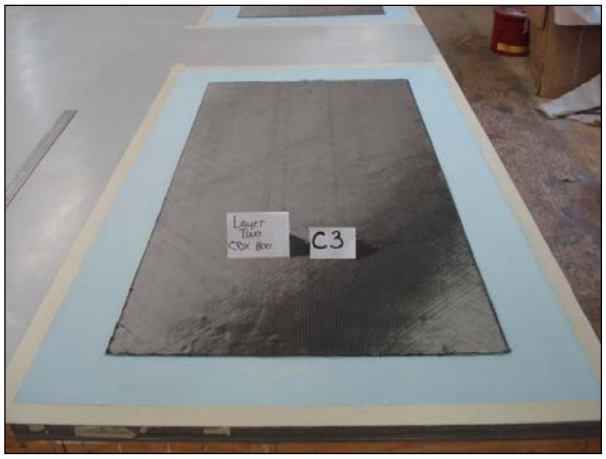
Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

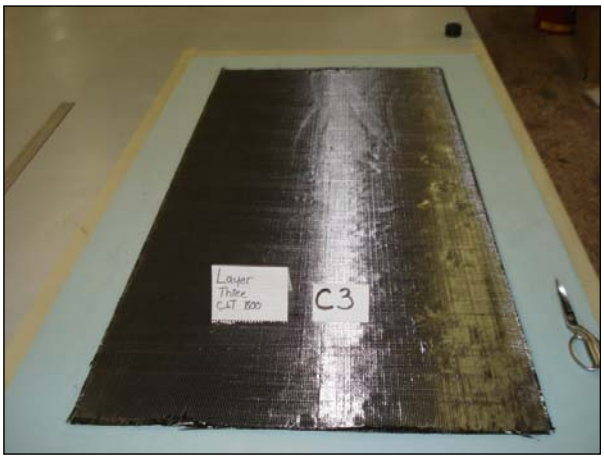
Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H160 (0.75”)			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (0.75”)			√
8		CLT 1800			√
9		CBX 1800			√

Picture Not Available



1st Layer – E-Veil

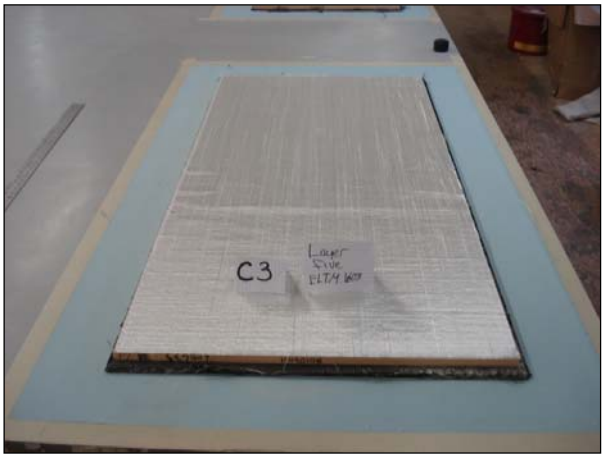
2nd Layer – CBX 1800





3rd Layer – CLT 1800

4th Layer – H160 (0.75”) Core



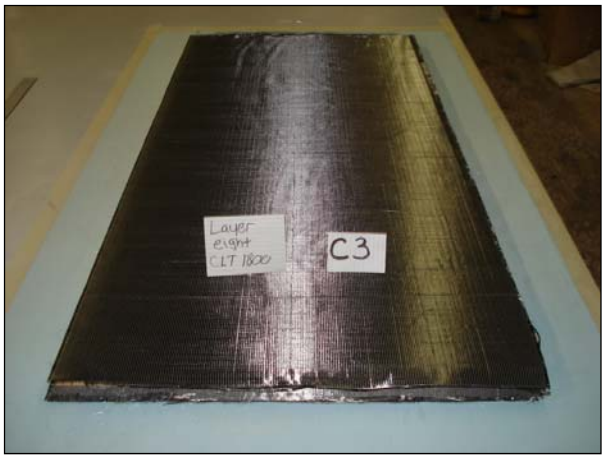
5th Layer – ELTM 1603



6th Layer – 1.5oz CFM



7th Layer – H100 (0.75”) Core



8th Layer – CLT 1800



9th Layer – CBX 1800

Project Number: ***0632***

Part Number: ***Config C3(1)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 03/02/2011 **Shop Temperature:** 68 °F

Name(s): Jason Wight **Humidity:** 63 %RH

Sara Boston

Start: 9:35 **AM** / PM Vacuum Level: 27 "of Hg

Stop: 9:50 **AM** / PM Vacuum Level: 27 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config C3(1)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 03/02/2011 **Shop Temperature:** 68 °F

Name(s): Jason Wight **Humidity:** 62 %RH

Sara Boston

Infusion: Resin: 94 °F

Start: 10:48 **AM** / PM Temp: 68 °F Vacuum Level: 27 "of Hg

Stop: 11:05 **AM** / PM Temp: 78 °F Vacuum Level: 27 "of Hg

Comments: Infused in 17 minutes

Project Number: ***0632***

Part Number: ***Config C3(2)***

Data Sheet for Infusing Composite Structures

Date: 03/01/2011 **Shop Temperature:** 72 °F

Name(s): Jason Wight **Humidity:** 64 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H160 (0.75")			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (0.75")			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config C3(2)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 03/02/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 63 %RH

Sara Boston

Start: 9:45 **AM** / PM Vacuum Level: 29.5 “of Hg

Stop: 10:00 **AM** / PM Vacuum Level: 29.5 “of Hg

(Duration ≥ 15 min) (Leakage ≤ 1” of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config C3(2)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 03/02/2011 **Shop Temperature:** 69 °F

Name(s): Jason Wight **Humidity:** 61 %RH

Sara Boston

Infusion: Resin: 104 °F

Start: 12:08 AM / **PM** Temp: 68 °F Vacuum Level: 29.5 "of Hg

Stop: 12:18 AM / **PM** Temp: 91 °F Vacuum Level: 29.5 "of Hg

Comments: Infused in 10 minutes

Project Number: ***0632***

Part Number: ***Config C3(3)***

Data Sheet for Infusing Composite Structures

Date: 03/01/2011 **Shop Temperature:** 72 °F

Name(s): Jason Wight **Humidity:** 64 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H160 (0.75”)			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (0.75”)			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config C3(3)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 03/02/2011 **Shop Temperature:** 68 °F

Name(s): Jason Wight **Humidity:** 63 %RH

Sara Boston

Start: 9:35 **AM** / PM Vacuum Level: 28.5 "of Hg

Stop: 9:50 **AM** / PM Vacuum Level: 28.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config C3(3)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 03/02/2011 **Shop Temperature:** 70 °F

Name(s): Jason Wight **Humidity:** 60 %RH

Sara Boston

Infusion: Resin: 100 °F

Start: 1:00 AM / **PM** Temp: 69 °F Vacuum Level: 28.5 “of Hg

Stop: 1:12 AM / **PM** Temp: 82 °F Vacuum Level: 28.5 “of Hg

Comments: Infused in 12 minutes

Project Number: ***0632***

Part Number: ***Config C3(4)***

Data Sheet for Infusing Composite Structures

Date: 03/01/2011 **Shop Temperature:** 72 °F

Name(s): Jason Wight **Humidity:** 64 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H160 (0.75”)			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (0.75”)			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config C3(4)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 03/02/2011 **Shop Temperature:** 68 °F

Name(s): Jason Wight **Humidity:** 63 %RH

Sara Boston

Start: 9:35 **AM** / PM Vacuum Level: 28.5 “of Hg

Stop: 9:50 **AM** / PM Vacuum Level: 28.5 “of Hg

(Duration ≥ 15 min) (Leakage ≤ 1” of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config C3(4)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 03/02/2011 **Shop Temperature:** 70 °F

Name(s): Jason Wight **Humidity:** 58 %RH

Sara Boston

Infusion: Resin: 98 °F

Start: 1:36 AM / **PM** Temp: 68 °F Vacuum Level: 28.5 "of Hg

Stop: 1:47 AM / **PM** Temp: 89 °F Vacuum Level: 28.5 "of Hg

Comments: Infused in 11 minutes

Project Number: ***0632***

Part Number: ***Config C(1)***

Data Sheet for Infusing Composite Structures

Date: 01/28/2011 **Shop Temperature:** 65 °F

Name(s): Jason Wight **Humidity:** 47 %RH

Sara Boston

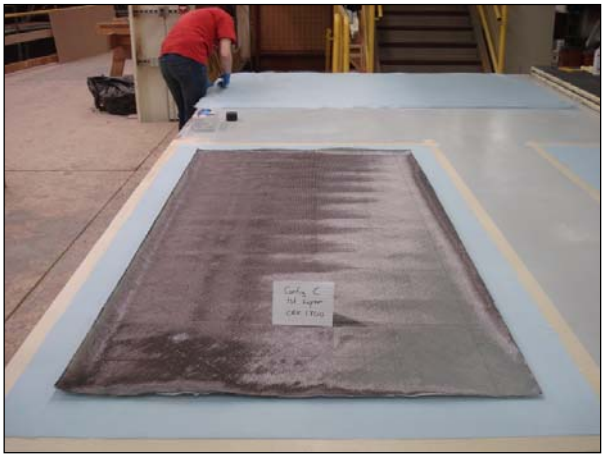
LAY-UP EXAMINATION

Panel Lay-Up:

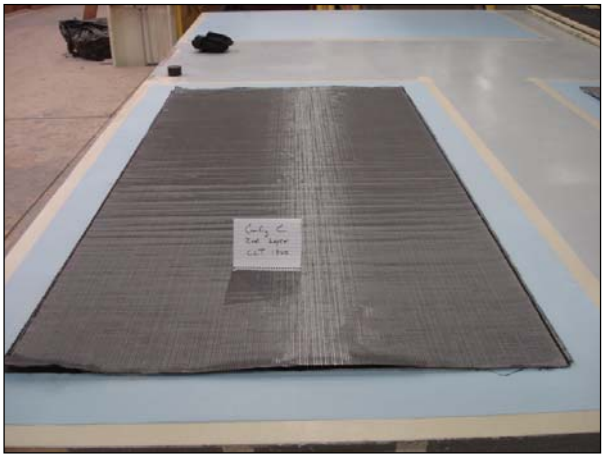
Ply 1 is ply closest to table/mold

Add sheets if necessary

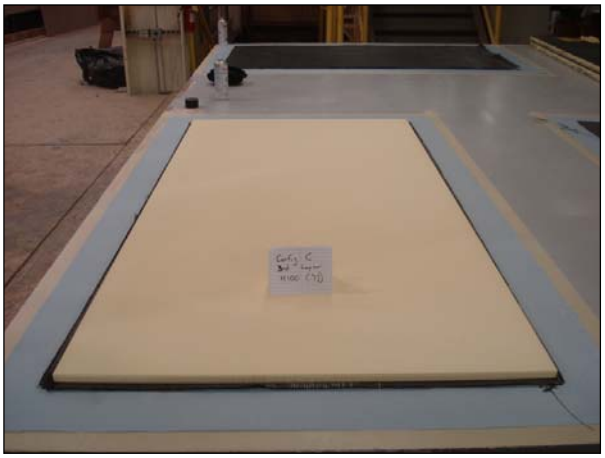
Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H100 (0.75")			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (0.75")			√
8		CLT 1800			√
9		CBX 1800			√



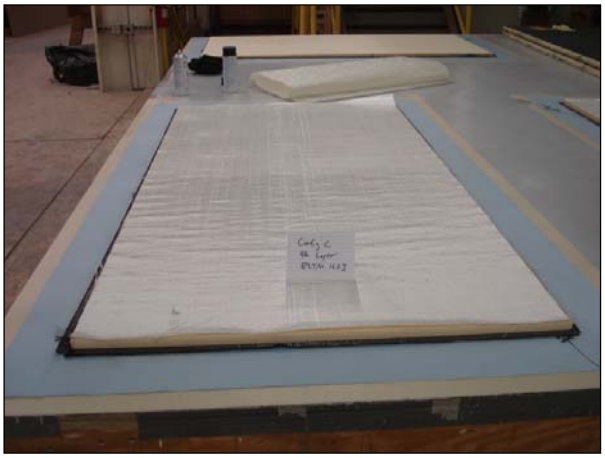
1st Layer – CBX 1800



2nd Layer – CLT 1800



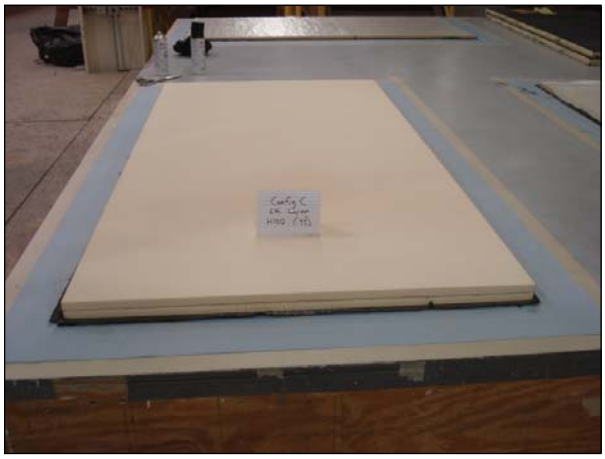
3rd Layer – H100 (0.75”) Core



4th Layer – E LTM 1603



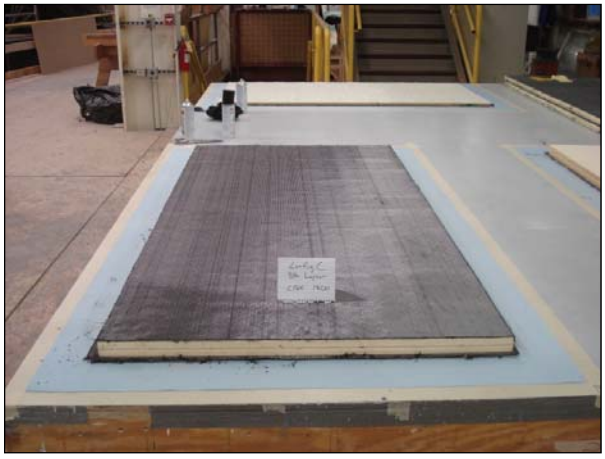
5th Layer – 1.5oz CFM



6th Layer – H100 (0.75") Core



7th Layer – CLT 1800



8th Layer – CBX 1800

Project Number: ***0632***

Part Number: ***Config C(1)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 01/28/2011 **Shop Temperature:** 65 °F

Name(s): Jason Wight **Humidity:** 47 %RH

Sara Boston

Start: 6:07 **AM** / PM Vacuum Level: 28.5 "of Hg

Stop: 6:30 **AM** / PM Vacuum Level: 28.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config C(1)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 01/28/2011 **Shop Temperature:** 65.5 °F

Name(s): Jason Wight **Humidity:** 47 %RH

Sara Boston

Infusion: Resin: 70.3 °F

Start: 6:58 **AM** / PM Temp: 64.5 °F Vacuum Level: 27.5 "of Hg

Stop: 7:40 **AM** / PM Temp: 71 °F Vacuum Level: 27.5 "of Hg

Comments: Infused in 42 minutes

Project Number: ***0632***

Part Number: ***Config C(2)***

Data Sheet for Infusing Composite Structures

Date: 01/28/2011 **Shop Temperature:** 65 °F

Name(s): Jason Wight **Humidity:** 47 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H100 (0.75")			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (0.75")			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config C(2)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 01/28/2011 **Shop Temperature:** 65 °F

Name(s): Jason Wight **Humidity:** 47 %RH

Sara Boston

Start: 6:08 **AM** / PM Vacuum Level: 29.5 “of Hg

Stop: 6:30 **AM** / PM Vacuum Level: 29.5 “of Hg

(Duration ≥ 15 min) (Leakage ≤ 1” of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config C(2)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 01/28/2011 **Shop Temperature:** 65.5 °F

Name(s): Jason Wight **Humidity:** 47 %RH

Sara Boston

Infusion: Resin: 70.3 °F

Start: 7:06 **AM** / PM Temp: 64 °F Vacuum Level: 29.5 "of Hg

Stop: 7:46 **AM** / PM Temp: 72 °F Vacuum Level: 29.5 "of Hg

Comments: Infused in 40 minutes

Project Number: ***0632***

Part Number: ***Config C(3)***

Data Sheet for Infusing Composite Structures

Date: 02/02/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 50 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H100 (0.75”)			√
5		ELTM 1603			√
6		1.5oz CFM			√
7		H100 (0.75”)			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config C(3)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 02/02/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 50 %RH

Sara Boston

Start: 6:30 **AM** / PM Vacuum Level: 27.5 "of Hg

Stop: 6:45 **AM** / PM Vacuum Level: 27.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config C(3)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 02/02/2011 **Shop Temperature:** 71.5 °F

Name(s): Jason Wight **Humidity:** 51 %RH

Sara Boston

Infusion: Resin: 82 °F

Start: 10:48 **AM** / PM Temp: 71 °F Vacuum Level: 29.5 "of Hg

Stop: 11:13 **AM** / PM Temp: 81 °F Vacuum Level: 29.5 "of Hg

Comments: Infused in 25 minutes

Project Number: ***0632***

Part Number: ***Config D2(1)***

Data Sheet for Infusing Composite Structures

Date: 02/17/2011 **Shop Temperature:** 69 °F

Name(s): Jason Wight **Humidity:** 64 %RH

Sara Boston

LAY-UP EXAMINATION

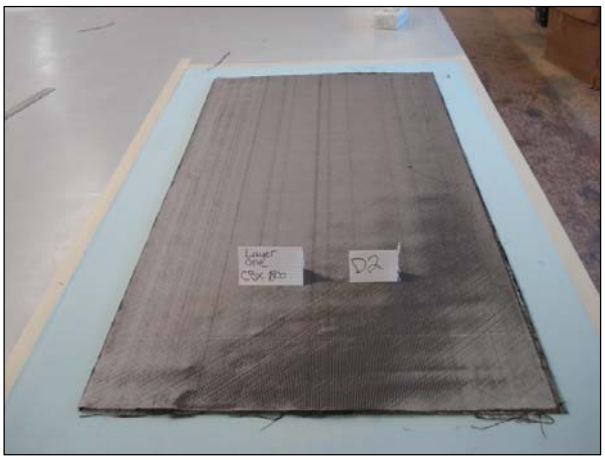
Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

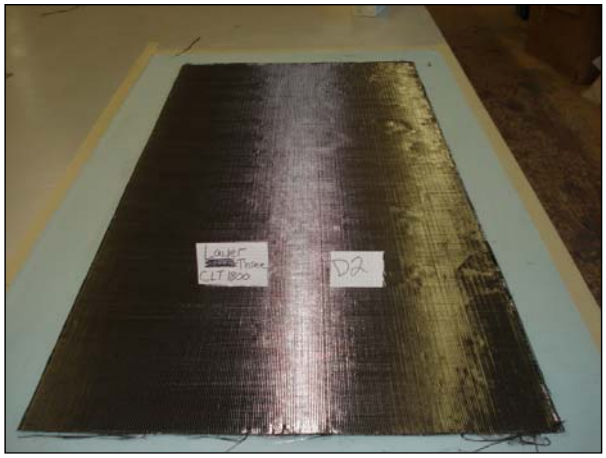
Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H100 (1.0")			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H130 (0.5")			√
8		CLT 1800			√
9		CBX 1800			√

Picture Not Available



1st Layer – E-Veil

2nd Layer – CBX 1800





3rd Layer – CLT 1800

4th Layer – H100 (1.0") Core



5th Layer – ELTM 1603



6th Layer – 1.5oz CFM



7th Layer – H130 (0.5") Core

Picture Not Available

8th Layer – CLT 1800



9th Layer – CBX 1800

Project Number: ***0632***

Part Number: ***Config D2(1)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 02/17/2011 **Shop Temperature:** 69 °F

Name(s): Jason Wight **Humidity:** 64 %RH

Sara Boston

Start: 7:55 **AM** / PM Vacuum Level: 29.5 "of Hg

Stop: 8:10 **AM** / PM Vacuum Level: 29.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config D2(1)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 02/17/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 60 %RH

Sara Boston

Infusion: Resin: 88 °F

Start: 9:25 **AM** / PM Temp: 71 °F Vacuum Level: 29.5 "of Hg

Stop: 9:43 **AM** / PM Temp: 84 °F Vacuum Level: 29.5 "of Hg

Comments: Infused in 18 minutes

Project Number: ***0632***

Part Number: ***Config D2(2)***

Data Sheet for Infusing Composite Structures

Date: 02/17/2011 **Shop Temperature:** 69 °F

Name(s): Jason Wight **Humidity:** 64 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H100 (1.0")			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H130 (0.5")			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config D2(2)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 02/17/2011 **Shop Temperature:** 69 °F

Name(s): Jason Wight **Humidity:** 64 %RH

Sara Boston

Start: 7:55 **AM** / PM Vacuum Level: 27 "of Hg

Stop: 8:10 **AM** / PM Vacuum Level: 27 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config D2(2)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 02/17/2011 **Shop Temperature:** 72 °F

Name(s): Jason Wight **Humidity:** 60 %RH

Sara Boston

Infusion: Resin: 91 °F

Start: 9:55 **AM** / PM Temp: 73 °F Vacuum Level: 27 "of Hg

Stop: 10:15 **AM** / PM Temp: 85 °F Vacuum Level: 27 "of Hg

Comments: Infused in 20 minutes

Project Number: ***0632***

Part Number: ***Config D2(3)***

Data Sheet for Infusing Composite Structures

Date: 02/17/2011 **Shop Temperature:** 69 °F

Name(s): Jason Wight **Humidity:** 64 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H100 (1.0")			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H130 (0.5")			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config D2(3)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 02/17/2011 **Shop Temperature:** 69 °F

Name(s): Jason Wight **Humidity:** 64 %RH

Sara Boston

Start: 8:15 **AM** / PM Vacuum Level: 28.5 "of Hg

Stop: 8:30 **AM** / PM Vacuum Level: 28.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config D2(3)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 02/17/2011 **Shop Temperature:** 73 °F

Name(s): Jason Wight **Humidity:** 58 %RH

Sara Boston

Infusion: Resin: 96 °F

Start: 10:27 **AM** / PM Temp: 75 °F Vacuum Level: 28.5 “of Hg

Stop: 10:43 **AM** / PM Temp: 86 °F Vacuum Level: 28.5 “of Hg

Comments: Infused in 16 minutes

Project Number: ***0632***

Part Number: ***Config D3(1)***

Data Sheet for Infusing Composite Structures

Date: 03/22/2011 **Shop Temperature:** 72 °F

Name(s): Patrick Sanborn **Humidity:** 72 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		M100 (1.0")			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H160 (0.5")			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config D3(1)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 03/22/2011 **Shop Temperature:** 72 °F

Name(s): Patrick Sanborn **Humidity:** 72 %RH

Start: 1:45 AM / **PM** Vacuum Level: 29 "of Hg

Stop: 2:00 AM / **PM** Vacuum Level: 29 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config D3(1)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 03/22/2011 **Shop Temperature:** 72 °F

Name(s): Patrick Sanborn **Humidity:** 72 %RH

Sara Boston

Infusion: Resin: 77.8 °F

Start: 2:43 AM / **PM** Temp: 72 °F Vacuum Level: 29 "of Hg

Stop: 3:03 AM / **PM** Temp: 75.2 °F Vacuum Level: 29 "of Hg

Comments: Infused in 20 minutes

Project Number: ***0632***

Part Number: ***Config D3(2)***

Data Sheet for Infusing Composite Structures

Date: 03/22/2011 **Shop Temperature:** 72 °F

Name(s): Patrick Sanborn **Humidity:** 72 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		M100 (1.0")			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H160 (0.5")			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config D3(2)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 03/22/2011 **Shop Temperature:** 72 °F

Name(s): Patrick Sanborn **Humidity:** 72 %RH

Start: 1:30 AM / **PM** Vacuum Level: 27 "of Hg

Stop: 1:45 AM / **PM** Vacuum Level: 26.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config D3(2)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 03/22/2011 **Shop Temperature:** 72 °F

Name(s): Patrick Sanborn **Humidity:** 72 %RH

Sara Boston

Infusion: Resin: 78 °F

Start: 2:44 AM / **PM** Temp: 71.8 °F Vacuum Level: 27 "of Hg

Stop: 3:02 AM / **PM** Temp: 75.3 °F Vacuum Level: 27 "of Hg

Comments: Infused in 18 minutes

Project Number: ***0632***

Part Number: ***Config D3(3)***

Data Sheet for Infusing Composite Structures

Date: 03/22/2011 **Shop Temperature:** 70 °F

Name(s): Patrick Sanborn **Humidity:** 72 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		M100 (1.0")			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H160 (0.5")			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config D3(3)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 03/22/2011 **Shop Temperature:** 66 °F

Name(s): Patrick Sanborn **Humidity:** 72 %RH

Start: 6:30 **AM** / PM Vacuum Level: 29 "of Hg

Stop: 6:45 **AM** / PM Vacuum Level: 29 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config D3(3)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 03/23/2011 **Shop Temperature:** 68 °F

Name(s): Patrick Sanborn **Humidity:** 67 %RH

Sara Boston

Infusion: Resin: 92 °F

Start: 8:24 **AM** / PM Temp: 67 °F Vacuum Level: 29 "of Hg

Stop: 8:40 **AM** / PM Temp: 80 °F Vacuum Level: 29 "of Hg

Comments: Infused in 16 minutes

Project Number: ***0632***

Part Number: ***Config D3(4)***

Data Sheet for Infusing Composite Structures

Date: 03/22/2011 **Shop Temperature:** 70 °F

Name(s): Patrick Sanborn **Humidity:** 72 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		M100 (1.0”)			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H160 (0.5”)			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config D3(4)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 03/23/2011 **Shop Temperature:** 66 °F

Name(s): Patrick Sanborn **Humidity:** 71 %RH

Sara Boston

Start: 6:45 **AM** / PM Vacuum Level: 27 "of Hg

Stop: 7:00 **AM** / PM Vacuum Level: 26.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config D3(4)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 03/23/2011 **Shop Temperature:** 70 °F

Name(s): Patrick Sanborn **Humidity:** 63 %RH

Sara Boston

Infusion: Resin: 97 °F

Start: 9:24 **AM** / PM Temp: 70 °F Vacuum Level: 27 "of Hg

Stop: 9:40 **AM** / PM Temp: 81 °F Vacuum Level: 27 "of Hg

Comments: Infused in 16 minutes

Project Number: ***0632***

Part Number: ***Config D4(1)***

Data Sheet for Infusing Composite Structures

Date: 03/09/2011 **Shop Temperature:** 69 °F

Name(s): Patrick Sanborn **Humidity:** 46 %RH

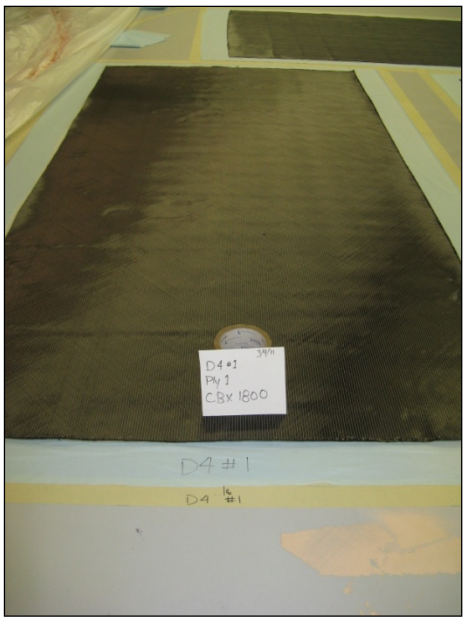
LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		M100 (1.0")			√
5		1.5oz CFM			√
6		E LTM 1603			√
7		H100 (0.5")			√
8		CLT 1800			√
9		CBX 1800			√



1st Layer – CBX 1800



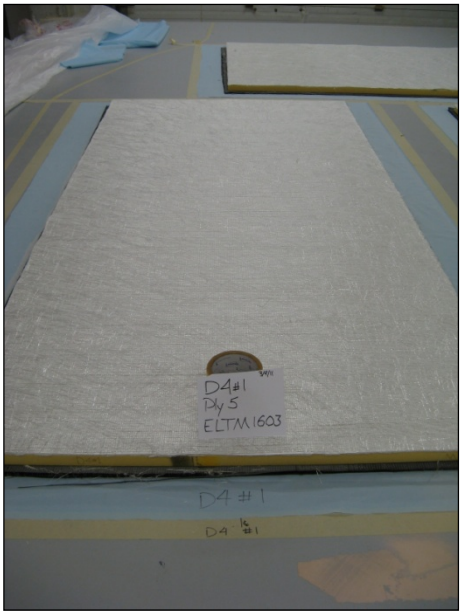
2nd Layer – CLT 1800



3rd Layer – M100 (1.0") Core



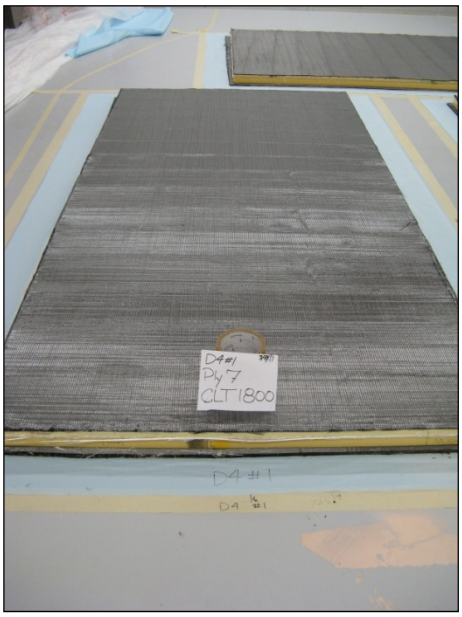
4th Layer – 1.5oz CFM



5th Layer – ELTM 1603



6th Layer – H100 (0.5") Core



7th Layer – CLT 1800



8th Layer – CBX 1800

Project Number: ***0632***

Part Number: ***Config D4(1)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 03/10/2011 **Shop Temperature:** 68 °F

Name(s): Jason Wight **Humidity:** NA %RH

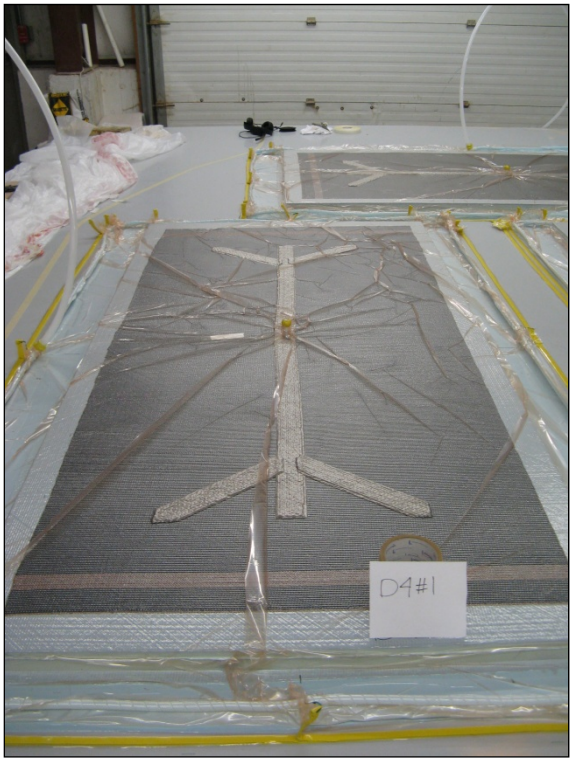
Sara Boston

Start: 12:02 AM / **PM** Vacuum Level: 30 "of Hg

Stop: 12:17 AM / **PM** Vacuum Level: 29 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



Project Number: ***0632***

Part Number: ***Config D4(1)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 03/10/2011 **Shop Temperature:** 69 °F

Name(s): Patrick Sanborn **Humidity:** NA %RH

Infusion: Resin: 86 °F

Start: 2:36 AM / **PM** Temp: 70 °F Vacuum Level: 30 "of Hg

Stop: 2:58 AM / **PM** Temp: 75 °F Vacuum Level: 30 "of Hg

Comments: Infused in 22 minutes

Project Number: ***0632***

Part Number: ***Config D4(2)***

Data Sheet for Infusing Composite Structures

Date: 03/09/2011 **Shop Temperature:** 69 °F

Name(s): Patrick Sanborn **Humidity:** 46 %RH

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		M100 (1.0")			√
5		1.5oz CFM			√
6		E LTM 1603			√
7		H100 (0.5")			√
8		CLT 1800			√
9		CBX 1800			√



1st Layer – CBX 1800



2nd Layer – CLT 1800



3rd Layer – M100 (1.0") Core



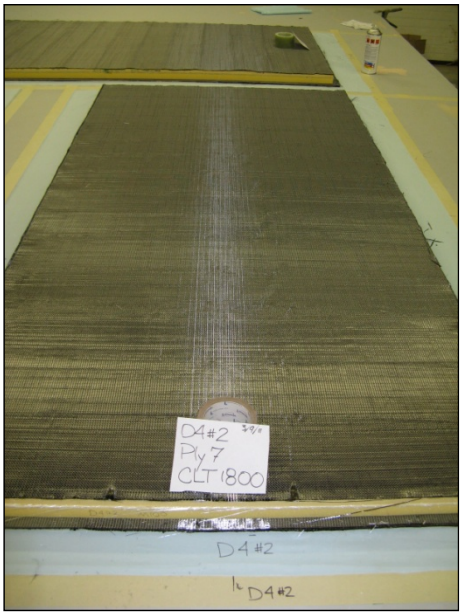
4th Layer – 1.5oz CFM



5th Layer – ELTM 1603



6th Layer – H100 (0.5") Core



7th Layer – CLT 1800



8th Layer – CBX 1800

Project Number: ***0632***

Part Number: ***Config D4(2)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 03/10/2011 **Shop Temperature:** 68 °F

Name(s): Patrick Sanborn **Humidity:** NA %RH

Start: 12:02 AM / **PM** Vacuum Level: 28 "of Hg

Stop: 12:18 AM / **PM** Vacuum Level: 27.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



Project Number: ***0632***

Part Number: ***Config D4(2)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 03/10/2011 **Shop Temperature:** 68 °F

Name(s): Patrick Sanborn **Humidity:** NA %RH

Infusion: Resin: 90 °F

Start: 1:21 AM / **PM** Temp: 70 °F Vacuum Level: 28 "of Hg

Stop: 1:44 AM / **PM** Temp: 79 °F Vacuum Level: 28 "of Hg

Comments: Infused in 23 minutes

Project Number: ***0632***

Part Number: ***Config D4(3)***

Data Sheet for Infusing Composite Structures

Date: 03/09/2011 **Shop Temperature:** 69 °F

Name(s): Patrick Sanborn **Humidity:** 46 %RH

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		M100 (1.0")			√
5		1.5oz CFM			√
6		E LTM 1603			√
7		H100 (0.5")			√
8		CLT 1800			√
9		CBX 1800			√



1st Layer – CBX 1800



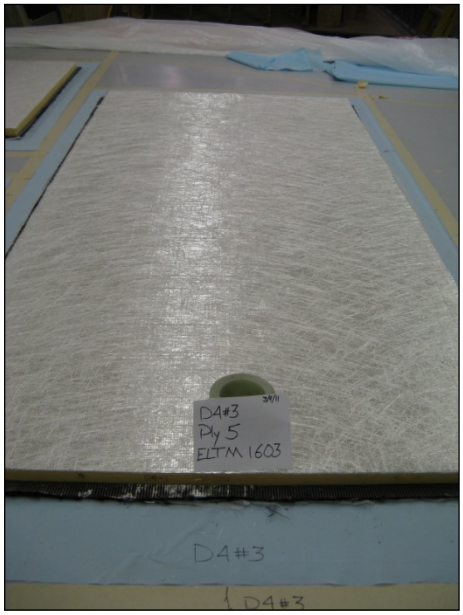
2nd Layer – CLT 1800



3rd Layer – M100 (1.0") Core



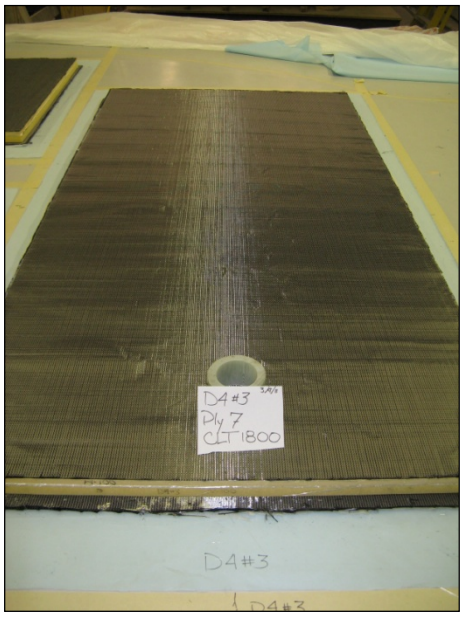
4th Layer – 1.5oz CFM



5th Layer – ELTM 1603



6th Layer – H100 (0.5") Core



7th Layer – CLT 1800



8th Layer – CBX 1800

Project Number: ***0632***

Part Number: ***Config D4(3)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 03/10/2011 **Shop Temperature:** 68 °F

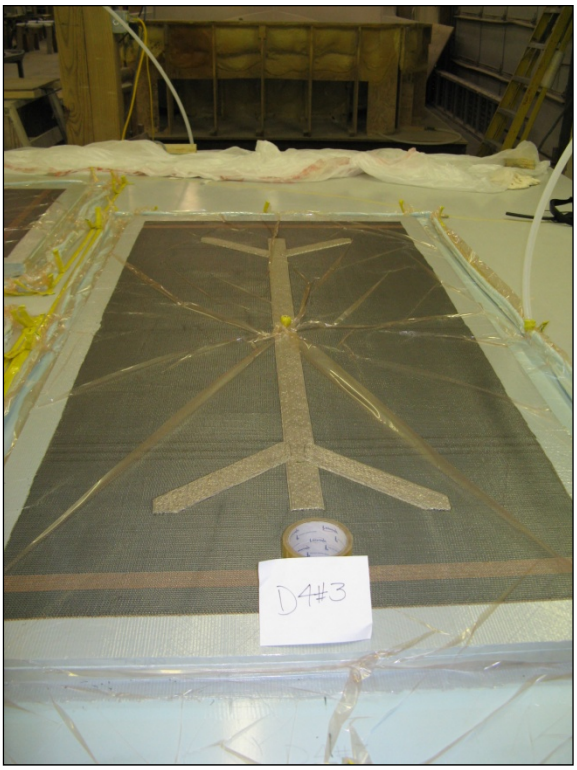
Name(s): Patrick Sanborn **Humidity:** NA %RH

Start: 12:02 AM / **PM** Vacuum Level: 28.5 "of Hg

Stop: 12:18 AM / **PM** Vacuum Level: 28.5 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



Project Number: ***0632***

Part Number: ***Config D4(3)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 03/10/2011 **Shop Temperature:** 68 °F

Name(s): Patrick Sanborn **Humidity:** NA %RH

Infusion:		Resin:	97 °F	
Start:	12:49 AM / **PM**	Temp:	69 °F	Vacuum Level: 28.5 “of Hg
Stop:	1:13 AM / **PM**	Temp:	79 °F	Vacuum Level: 28.5 “of Hg

Comments: Infused in 24 minutes

Project Number: ***0632***

Part Number: ***Config D(1)***

Data Sheet for Infusing Composite Structures

Date: 02/03/2011 **Shop Temperature:** 72.7 °F

Name(s): Jason Wight **Humidity:** 50 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

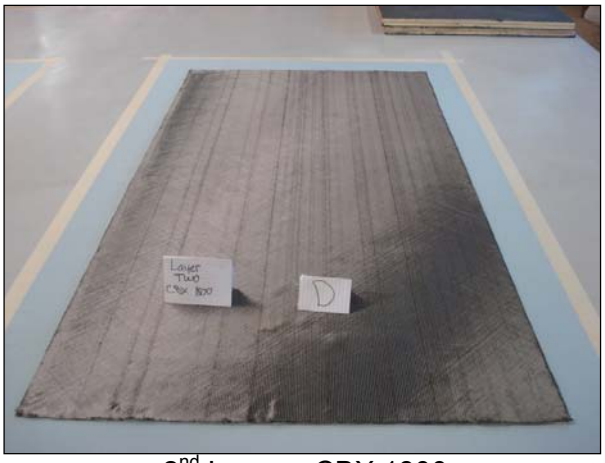
Ply 1 is ply closest to table/mold

Add sheets if necessary

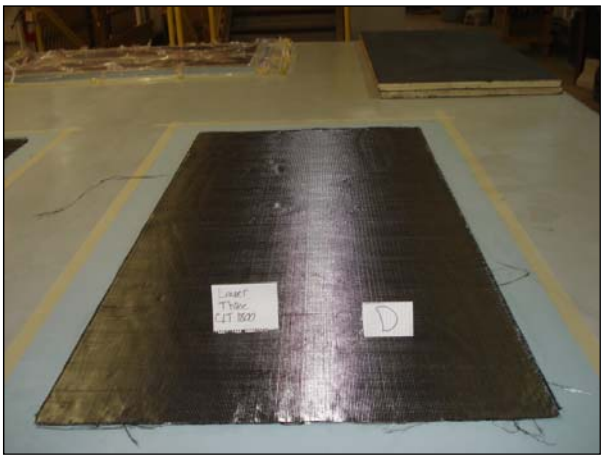
Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H100 (1.0")			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (0.5")			√
8		CLT 1800			√
9		CBX 1800			√

Picture Not Available

1st Layer – E-Veil



2nd Layer – CBX 1800



3rd Layer – CLT 1800



4th Layer – H100 (1.0") Core



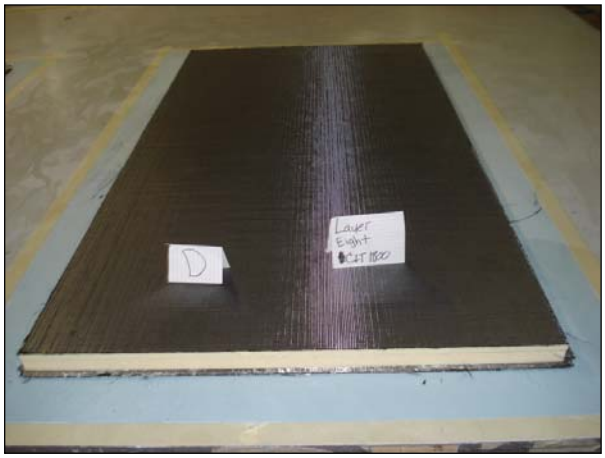
5th Layer – ELTM 1603



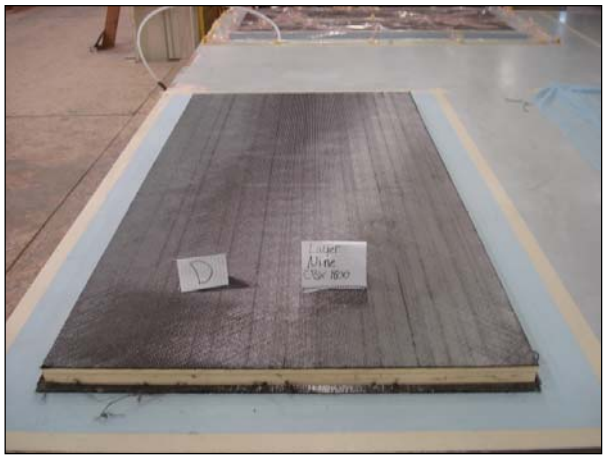
6th Layer – 1.5oz CFM



7th Layer – H100 (0.5") Core



8th Layer – CLT 1800



9th Layer – CBX 1800

Project Number: ***0632***

Part Number: ***Config D(1)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 02/04/2011 **Shop Temperature:** 64 °F

Name(s): Jason Wight **Humidity:** 59 %RH

Sara Boston

Start: 6:13 **AM** / PM Vacuum Level: 28.5 "of Hg

Stop: 6:28 **AM** / PM Vacuum Level: 28.3 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config D(1)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 02/04/2011 **Shop Temperature:** 71.3 °F

Name(s): Jason Wight **Humidity:** 51 %RH

Sara Boston

Infusion: Resin: 102 °F

Start: 9:57 **AM** / PM Temp: 73 °F Vacuum Level: 28.5 "of Hg

Stop: 10:07 **AM** / PM Temp: 95 °F Vacuum Level: 28.5 "of Hg

Comments: Infused in 10 minutes

Project Number: ***0632***

Part Number: ***Config D(2)***

Data Sheet for Infusing Composite Structures

Date: 02/03/2011 **Shop Temperature:** 72 °F

Name(s): Jason Wight **Humidity:** 50 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H100 (1.0")			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (0.5")			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config D(2)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 02/03/2011 **Shop Temperature:** 72 °F

Name(s): Jason Wight **Humidity:** 50 %RH

Sara Boston

Start: 1:18 AM / **PM** Vacuum Level: 30 "of Hg

Stop: 1:33 AM / **PM** Vacuum Level: 30 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config D(2)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 02/03/2011 **Shop Temperature:** 72 °F

Name(s): Jason Wight **Humidity:** 50 %RH

Sara Boston

Infusion: Resin: 90 °F

Start: 1:36 AM / **PM** Temp: 72 °F Vacuum Level: 30 "of Hg

Stop: 1:55 AM / **PM** Temp: 82 °F Vacuum Level: 30 "of Hg

Comments: Infused in 19 minutes

Project Number: ***0632***

Part Number: ***Config D(3)***

Data Sheet for Infusing Composite Structures

Date: 02/03/2011 **Shop Temperature:** 72 °F

Name(s): Jason Wight **Humidity:** 50 %RH

Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		E-Veil			√
2		CBX 1800			√
3		CLT 1800			√
4		H100 (1.0”)			√
5		E LTM 1603			√
6		1.5oz CFM			√
7		H100 (0.5”)			√
8		CLT 1800			√
9		CBX 1800			√

Project Number: ***0632***

Part Number: ***Config D(3)***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 02/03/2011 **Shop Temperature:** 72 °F

Name(s): Jason Wight **Humidity:** 50 %RH

Sara Boston

Start: 1:20 AM / **PM** Vacuum Level: 29 "of Hg

Stop: 1:37 AM / **PM** Vacuum Level: 29 "of Hg

(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

Project Number: ***0632***

Part Number: ***Config D(3)***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 02/03/2011 **Shop Temperature:** 72 °F

Name(s): Jason Wight **Humidity:** 50 %RH

Sara Boston

Infusion: Resin: 88 °F

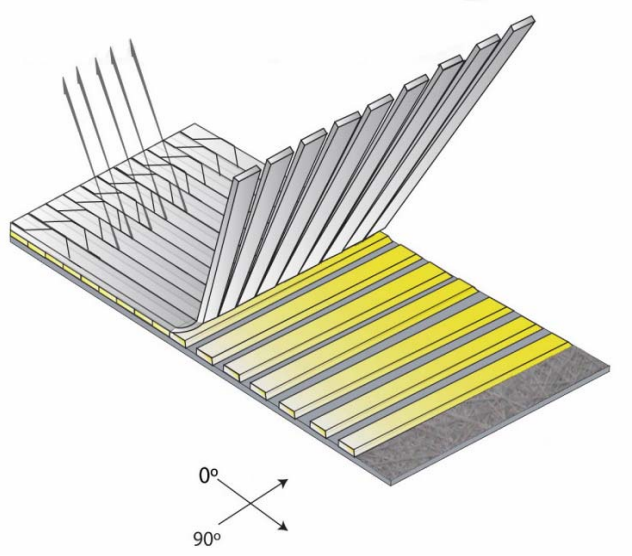
Start: 2:29 AM / **PM** Temp: 73 °F Vacuum Level: 29 "of Hg

Stop: 2:46 AM / **PM** Temp: 85 °F Vacuum Level: 29 "of Hg

Comments: Infused in 17 minutes

Appendix B
Sandwich Panel Material Data Sheets

VECTORPLY®
Performance Composite Reinforcements



E-LTM 1603

Fiber Type: E-Glass
Archtecture: 0º/90º Biaxial
Dry Thickness 0.027 in. / 0.69 mm
Total Weight: 18.96 oz/sq.yd / 643 g/sq.m

DNV

Roll Specifications			Fiber Architecture Data	
Roll Width:	Roll Weight:	Roll Length:	0 ° :	8.96 oz/sq.yd / 304 g/sq.m
50 in / 1270 mm	179 lb / 81 kg	106 yd / 97 m	45 ° :	n/a
			90 ° :	7.00 oz/sq.yd / 237 g/sq.m
			- 45 ° :	n/a
			Chopped Mat :	3.00 oz/sq.yd / 102 g/sq.m

1: Packaging: box or bag.
2: Weights do not include polyester stitching.

Laminated Properties	0 °	0 °
Laminate Weight		
(lb/sq.ft)	E-LTM 1603 Resin Infused	E-LTM 1603 Open Mold
Fiber	0.13	0.13
Resin	0.07	0.13
Total	0.20	0.26

Physical Properties		
	E-LTM 1603 Resin Infused	E-LTM 1603 Open Mold
Density (g/cc))	1.84	1.64
Fiber Content (% by Wt.)	66%	51%
Thickness (in)	0.021	0.030

Laminate Modulii		
(MSI)	E-LTM 1603 Resin Infused	E-LTM 1603 Open Mold
Ex	3.52	2.53
Ey	3.20	2.29
Gxy	0.43	0.30
Ex,flex.	3.26	2.34
Ey,flex.	2.96	2.11

Ultimate Stress		
(KSI)	E-LTM 1603 Resin Infused	E-LTM 1603 Open Mold
Long. Ten.	58	42
Long. Comp.	67	48
Trans. Ten.	53	37
Trans. Comp.	61	43
In-Plane Shear	11	10
Long. Flex.	84	60
Trans. Flex.	76	54

In-Plane Stiffness, "EA"		
10^3 lb/in	E-LTM 1603 Resin Infused	E-LTM 1603 Open Mold
(EA)x	74	76
(EA)y	67	69
(GA)xy	9	9

Ultimate In-Plane Load		
lb/in	E-LTM 1603 Resin Infused	E-LTM 1603 Open Mold
Long. Ten.	1,206	1,253
Long. Comp.	1,392	1,446
Trans. Ten.	1,095	1,130
Trans. Comp.	1,265	1,304
In-Plane Shear	222	297

Notes:

1: Resin infused laminate made with vinyl ester resin 200 cps viscosity @ 77º F.

2: Open mold laminate made with polyester resin.

3: All standard reinforcements should be infused with a flow aid or Vectorfusion® reinforcements.

VECTORPLY CORPORATION

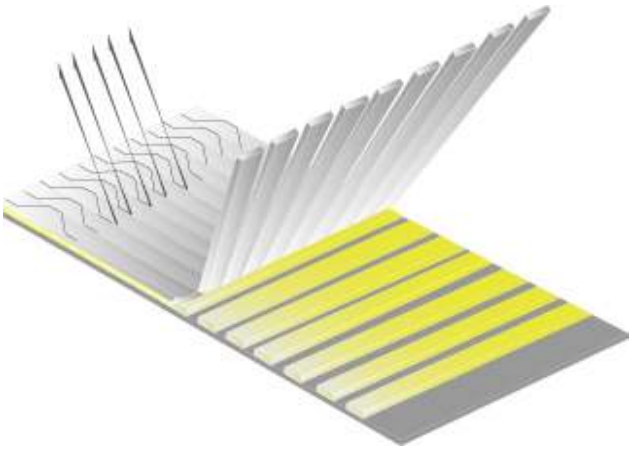
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VECTORPLY®
Performance Composite Reinforcements



E-LTCFM 2415-7P

Fiber Type: E-Glass
Architecture: 0º/90º Biaxial

Total Weight: 37.24 oz/sq.yd / 1263 g/sq.m

Roll Specifications			**Fiber Architecture Data**	
Roll Width:	Roll Weight:	Roll Length:	0 ° :	12.22 oz/sq.yd / 414 g/sq.m
50 in. / 1270 mm	164 lbs / 75 kg	50 yd / 46 m	45 ° :	n/a
			90 ° :	11.52 oz/sq.yd / 391 g/sq.m
			- 45 ° :	n/a
			Continuous Filament Mat:	13.5 oz/sq.yd / 458 g/sq.m

* Packaging: Box or Bag

**Total weight refers to reinforcement material only (does not include stitching weight).

Disclaimer:

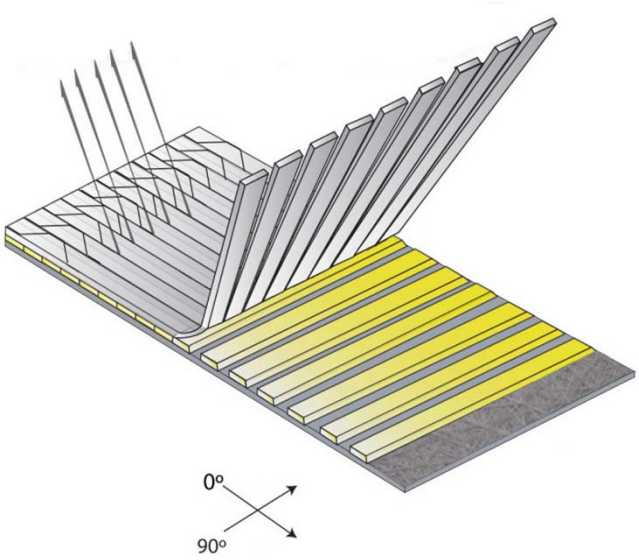
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36868

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VECTORPLY®
Performance Composite Reinforcements



E-LTM 3610

Fiber Type: E-Glass
Architecture: 0/90 Biaxial
Dry Thickness: 0.055 in. / 1.40 mm
Total Weight: 44.84 oz/sq.yd / 1520 g/sq.m

Roll Specifications			Fiber Architecture Data	
Roll Width:	Roll Weight:	Roll Length:	0 ° :	17.92 oz/sq.yd / 608 g/sq.m
50 in / 1270 mm	198 lb / 90 kg	50 yd / 46 m	45 ° :	n/a
			90 ° :	17.92 oz/sq.yd / 608 g/sq.m
			-45 ° :	n/a
			Chopped Mat :	9.00 oz/sq.yd / 305 g/sq.m

1: Packaging: box or bag.
2: Weights do not include polyester stitching.

Laminated Properties	0 °	0 °
Laminate Weight		
(lb/sq.ft)	E-LTM 3610 Resin Infused	E-LTM 3610 Open Mold
Fiber	0.31	0.31
Resin	0.15	0.33
Total	0.46	0.64

Physical Properties		
	E-LTM 3610 Resin Infused	E-LTM 3610 Open Mold
Density (g/cc))	1.87	1.62
Fiber Content (% by Wt.)	68%	49%
Thickness (in)	0.047	0.076

Laminate Modulii		
(MSI)	E-LTM 3610 Resin Infused	E-LTM 3610 Open Mold
Ex	3.38	2.27
Ey	3.38	2.27
Gxy	0.66	0.45
Ex,flex.	3.21	2.16
Ey,flex.	3.21	2.16

Ultimate Stress		
(KSI)	E-LTM 3610 Resin Infused	E-LTM 3610 Open Mold
Long. Ten.	53	35
Long. Comp.	53	35
Trans. Ten.	55	37
Trans. Comp.	57	39
In-Plane Shear	15	10
Long. Flex.	69	46
Trans. Flex.	69	46

In-Plane Stiffness, "EA"		
10^3 lb/in	E-LTM 3610 Resin Infused	E-LTM 3610 Open Mold
(EA)x	160	172
(EA)y	160	172
(GA)xy	31	34

Ultimate In-Plane Load		
lb/in	E-LTM 3610 Resin Infused	E-LTM 3610 Open Mold
Long. Ten.	2,485	2,669
Long. Comp.	2,485	2,669
Trans. Ten.	2,624	2,817
Trans. Comp.	2,718	2,919
In-Plane Shear	707	780

Notes:

1: Resin infused laminate made with a poly / vinyl ester resin blend.

2: Open mold laminate made with poly / vinyl ester resin blend.

3: All standard reinforcements should be infused with a flow aid or Vectorfusion® reinforcements.

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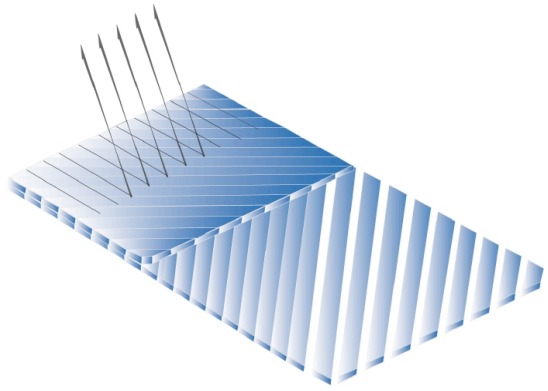
REV: 5/3/2011

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VECTORPLY®
Performance Composite Reinforcements



C-BX 1200

Fiber Type:	Carbon
Architecture:	+45º/-45º Double Bias
Dry Thickness:	0.024 in. / 0.610 mm
Total Weight:	11.80 oz/sq.yd / 400.2 g/sq.m

VECTORULTRA™

Roll Specifications

Roll Width:	Roll Weight:	Roll Length:
50 in / 1270 mm	85 lb / 39 kg	82 yd / 75 m

Fiber Architecture Data

0 ° :	n/a
45 ° :	5.90 oz/sq.yd / 200 g/sq.m
90 ° :	n/a
- 45 ° :	5.90 oz/sq.yd / 200 g/sq.m
Chopped Mat:	n/a

1: Packaging: box or bag.
2: Weights do not include polyester stitching.

Laminated Properties 45 ° 45 °

Laminate Weight (lb/sq.ft)	C-BX 1200 Resin Infused	C-BX 1200 Open Mold
Fiber	0.08	0.08
Resin	0.04	0.10
Total	0.13	0.18

Physical Properties	C-BX 1200 Resin Infused	C-BX 1200 Open Mold
Density (g/cc))	1.53	1.41
Fiber Content (% by Wt.)	65%	45%
Thickness (in)	0.016	0.025

Laminate Modulii		
(MSI)	C-BX 1200 Resin Infused	C-BX 1200 Open Mold
Ex	8.53	5.69
Ey	8.53	5.69
Gxy	0.37	0.25
Ex,flex.	8.10	5.40
Ey,flex.	8.10	5.40

Ultimate Stress		
(KSI)	C-BX 1200 Resin Infused	C-BX 1200 Open Mold
Long. Ten.	81	54
Long. Comp.	74	50
Trans. Ten.	81	54
Trans. Comp.	74	50
In-Plane Shear	7	5
Long. Flex.	83	55
Trans. Flex.	83	55

In-Plane Stiffness, "EA"		
10^3 lb/in	C-BX 1200 Resin Infused	C-BX 1200 Open Mold
(EA)x	135	141
(EA)y	135	141
(GA)xy	6	6

Ultimate In-Plane Load		
lb/in	C-BX 1200 Resin Infused	C-BX 1200 Open Mold
Long. Ten.	1,280	1,334
Long. Comp.	1,183	1,233
Trans. Ten.	1,280	1,334
Trans. Comp.	1,183	1,233
In-Plane Shear	118	122

Notes:

1: Resin infused laminate made with vinyl ester resin 200 cps viscosity @ 77º F.

2: Open mold laminate made with polyester resin.

3: All standard reinforcements should be infused with a flow aid or Vectorfusion® reinforcements.

VECTORPLY CORPORATION

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Technical Service Office

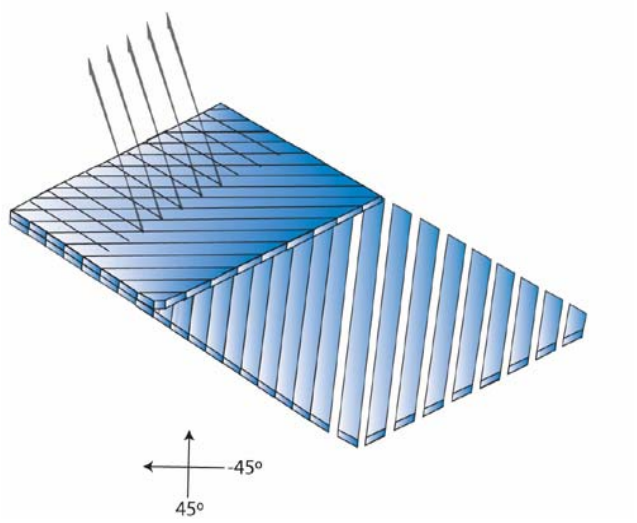
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VECTORPLY®
Performance Composite Reinforcements



C-BX 1800

Fiber Type: Carbon
Archtecture: +45°/-45° Double Bias
Dry Thickness 0.035 in. / 0.889 mm
Total Weight: 17.11 oz/sq.yd / 580.2 g/sq.m

VECTORULTRA™

Lloyd's Register APPROVED PRODUCT

Roll Specifications			Fiber Architecture Data	
Roll Width:	Roll Weight:	Roll Length:	0 ° :	n/a
50 in / 1270 mm	113 lb / 51 kg	75 yd / 69 m	45 ° :	8.56 oz/sq.yd / 290 g/sq.m
			90 ° :	n/a
			- 45 ° :	8.56 oz/sq.yd / 290 g/sq.m
			Chopped Mat :	n/a

1: Packaging: box or bag.
2: Weights do not include polyester stitching.

Laminated Properties	45 °	45 °
Laminate Weight		
(lb/sq.ft)	C-BX 1800 Resin Infused	C-BX 1800 Open Mold
Fiber	0.12	0.12
Resin	0.06	0.15
Total	0.18	0.26

Physical Properties		
	C-BX 1800 Resin Infused	C-BX 1800 Open Mold
Density (g/cc))	1.53	1.41
Fiber Content (% by Wt.)	65%	45%
Thickness (in)	0.023	0.036

Laminate Modulii		
(MSI)	C-BX 1800 Resin Infused	C-BX 1800 Open Mold
Ex	8.53	5.69
Ey	8.53	5.69
Gxy	0.37	0.25
Ex,flex.	8.10	5.40
Ey,flex.	8.10	5.40

Ultimate Stress		
(KSI)	C-BX 1800 Resin Infused	C-BX 1800 Open Mold
Long. Ten.	81	54
Long. Comp.	74	50
Trans. Ten.	81	54
Trans. Comp.	74	50
In-Plane Shear	7	5
Long. Flex.	83	55
Trans. Flex.	83	55

In-Plane Stiffness, "EA"		
10^3 lb/in	C-BX 1800 Resin Infused	C-BX 1800 Open Mold
(EA)x	196	205
(EA)y	196	205
(GA)xy	9	9

Ultimate In-Plane Load		
lb/in	C-BX 1800 Resin Infused	C-BX 1800 Open Mold
Long. Ten.	1,856	1,935
Long. Comp.	1,715	1,788
Trans. Ten.	1,856	1,935
Trans. Comp.	1,715	1,788
In-Plane Shear	172	177

Notes:

1: Resin infused laminate made with vinyl ester resin 200 cps viscosity @ 77º F.

2: Open mold laminate made with polyester resin.

3: All standard reinforcements should be infused with a flow aid or Vectorfusion® reinforcements.

VECTORPLY CORPORATION

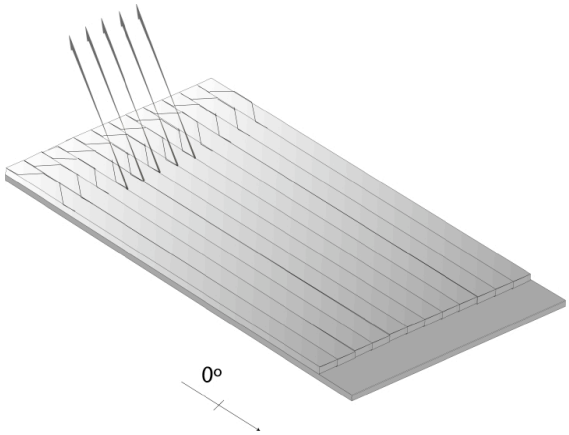
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VECTORPLY®
Performance Composite Reinforcements



C-LA 1812

Fiber Type: Carbon
Architecture: 0º Unidirectional
Dry Thickness: 0.039 in. / 0.991 mm
Total Weight: 18.80 oz/sq.yd / 637.4 g/sq.m

VECTORULTRA™

Roll Specifications			Fiber Architecture Data	
Roll Width:	Roll Weight:	Roll Length:	0 ° :	17.60 oz/sq.yd / 596.7 g/sq.m
50 in / 1270 mm	149 lb / 68 kg	89 yd / 81 m	45 ° :	n/a
			90 ° :	n/a
			- 45 ° :	n/a
			A-glass veil:	1.20 oz/sq.yd / 40.7 g/sq.m

1: Packaging: box or bag.
2: Weights do not include polyester stitching.

Laminated Properties	0 °	0 °
Laminate Weight		
(lb/sq.ft)	C-LA 1812 Resin Infused	C-LA 1812 Open Mold
Fiber	0.13	0.13
Resin	0.07	0.16
Total	0.20	0.29

Physical Properties		
	C-LA 1812 Resin Infused	C-LA 1812 Open Mold
Density (g/cc))	1.55	1.42
Fiber Content (% by Wt.)	65%	45%
Thickness (in)	0.025	0.039

Laminate Modulii		
(MSI)	C-LA 1812 Resin Infused	C-LA 1812 Open Mold
Ex	16.08	10.48
Ey	0.73	0.69
Gxy	0.41	0.27
Ex,flex.	15.21	9.89
Ey,flex.	0.69	0.65

Ultimate Stress		
(KSI)	C-LA 1812 Resin Infused	C-LA 1812 Open Mold
Long. Ten.	193	126
Long. Comp.	123	80
Trans. Ten.	14	13
Trans. Comp.	18	17
In-Plane Shear	11	7
Long. Flex.	123	80
Trans. Flex.	21	23

In-Plane Stiffness, "EA"		
10^3 lb/in	C-LA 1812 Resin Infused	C-LA 1812 Open Mold
(EA)x	402	410
(EA)y	18	27
(GA)xy	10	10

Ultimate In-Plane Load		
lb/in	C-LA 1812 Resin Infused	C-LA 1812 Open Mold
Long. Ten.	4,820	4,923
Long. Comp.	3,079	3,145
Trans. Ten.	338	496
Trans. Comp.	444	653
In-Plane Shear	280	290

Notes:

1: Resin infused laminate made with vinyl ester resin 200 cps viscosity @ 77º F.

2: Open mold laminate made with polyester resin.

3: All standard reinforcements should be infused with a flow aid or Vectorfusion® reinforcements.

VECTORPLY CORPORATION

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Technical Service Office

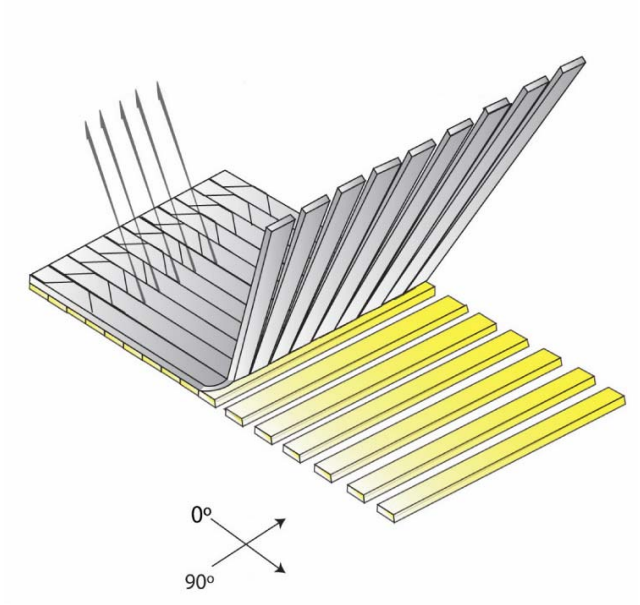
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VECTORPLY®
Performance Composite Reinforcements



C-LT 1800

Fiber Type: Carbon
Archtecture: 0º/90º Biaxial
Dry Thickness 0.035 in. / 0.89 mm
Total Weight: 18.58 oz/sq.yd / 630 g/sq.m

VECTORULTRA™

Lloyd's Register APPROVED PRODUCT

Roll Specifications			Fiber Architecture Data	
Roll Width:	Roll Weight:	Roll Length:	0 ° :	9.29 oz/sq.yd / 315 g/sq.m
50 in / 1270 mm	113 lb / 51 kg	69 yd / 63 m	45 ° :	n/a
			90 ° :	9.29 oz/sq.yd / 315 g/sq.m
			- 45 ° :	n/a
			Chopped Mat :	n/a

1: Packaging: box or bag.
2: Weights do not include polyester stitching.

Laminated Properties	0 °	0 °
Laminate Weight		
(lb/sq.ft)	C-LT 1800 Resin Infused	C-LT 1800 Open Mold
Fiber	0.13	0.13
Resin	0.07	0.16
Total	0.20	0.29

Physical Properties		
	C-LT 1800 Resin Infused	C-LT 1800 Open Mold
Density (g/cc))	1.53	1.41
Fiber Content (% by Wt.)	65%	45%
Thickness (in)	0.025	0.039

Laminate Modulii		
(MSI)	C-LT 1800 Resin Infused	C-LT 1800 Open Mold
Ex	9.10	6.06
Ey	9.10	6.06
Gxy	0.37	0.25
Ex,flex.	8.65	5.75
Ey,flex.	8.65	5.75

Ultimate Stress		
(KSI)	C-LT 1800 Resin Infused	C-LT 1800 Open Mold
Long. Ten.	100	67
Long. Comp.	71	47
Trans. Ten.	100	67
Trans. Comp.	71	47
In-Plane Shear	7	5
Long. Flex.	67	44
Trans. Flex.	67	44

In-Plane Stiffness, "EA"		
10^3 lb/in	C-LT 1800 Resin Infused	C-LT 1800 Open Mold
(EA)x	228	237
(EA)y	228	237
(GA)xy	9	10

Ultimate In-Plane Load		
lb/in	C-LT 1800 Resin Infused	C-LT 1800 Open Mold
Long. Ten.	2,509	2,608
Long. Comp.	1,780	1,850
Trans. Ten.	2,509	2,608
Trans. Comp.	1,780	1,850
In-Plane Shear	186	192

Notes:

1: Resin infused laminate made with vinyl ester resin 200 cps viscosity @ 77º F.

2: Open mold laminate made with polyester resin.

3: All standard reinforcements should be infused with a flow aid or Vectorfusion® reinforcements.

VECTORPLY CORPORATION

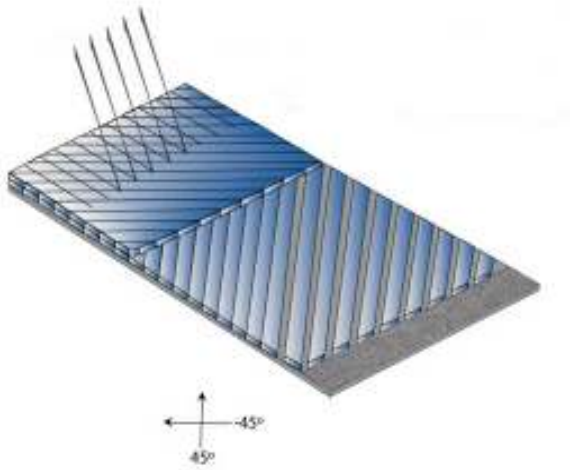
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VECTORPLY®
Performance Composite Reinforcements



K-BXM 1308

Fiber Type: E-Glass/Aramid
Architecture: +45º/-45º Double Bias

Total Weight: 22.02 oz/sq.yd / 747 g/sq.m

VECTORULTRA™

Roll Specifications			**Fiber Architecture Data**
Roll Width:	Roll Weight:	Roll Length:	
50 in. / 1270 mm	198 lbs /90 kg	102 yd / 93 m	Aramid 45 ° : 6.69 oz/sq.yd / 227 g/sq.m Aramid - 45 ° : 6.69 oz/sq.yd / 227 g/sq.m Chopped Mat : 8.64 oz/sq.yd / 293 g/sq.m

* Packaging: Box or Bag

**Total weight refers to reinforcement material only (does not include stitching weight).

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PRODUCT INFORMATION

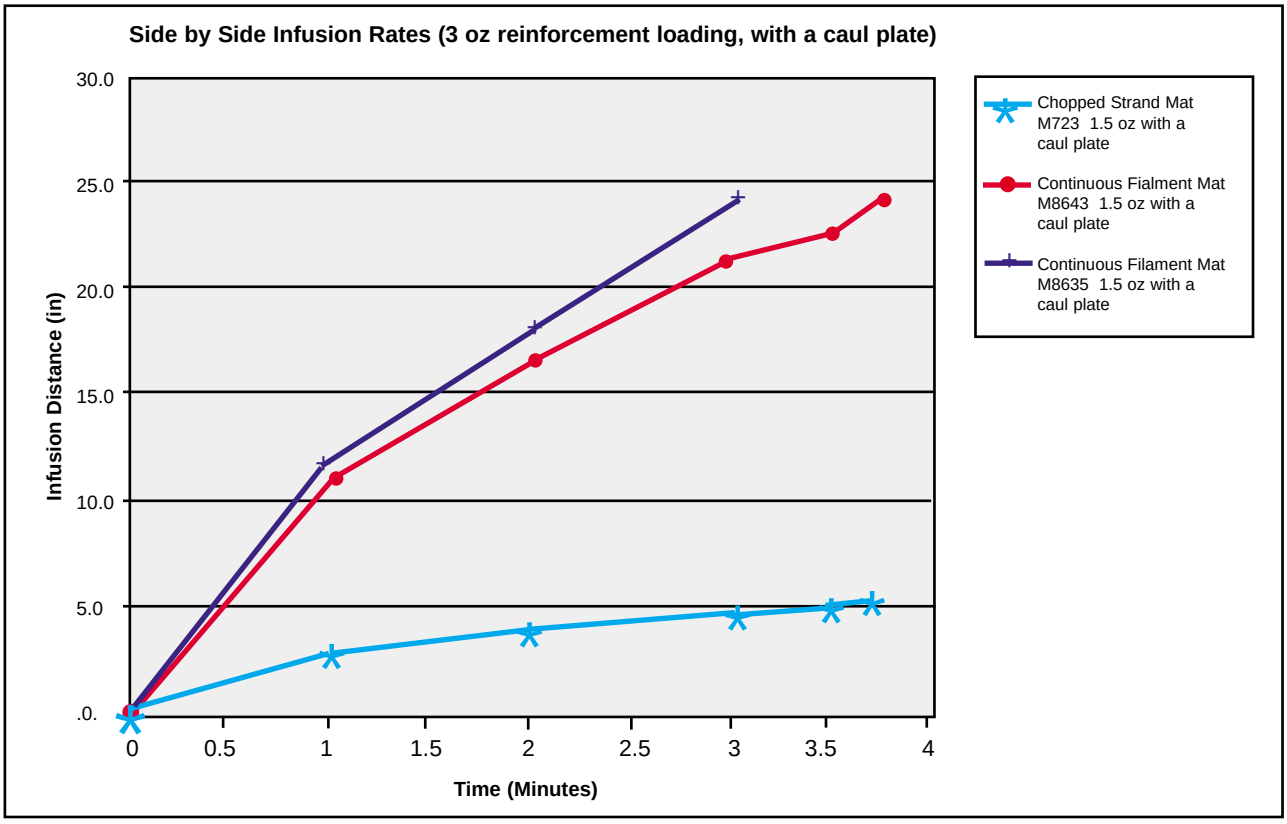
M 8635 Continuous Filament Mat
Reinforcement Mat for Infusion Molding

PRODUCT DESCRIPTION

Owens Corning M8635 Continuous Filament Mat is designed for use in infusion molding applications as alone or in combination with other reinforcements.
It consists of continuous fibers randomly oriented in multiple layers with a suitable bonding resin and silane coupling agent. M 8635 is available in both normal E glass and with Advantex®, glass, Owens Corning's trademarked corrosion resistant E glass.

FEATURES

- Rapid resin infusion
- Thermoset Binder which provides stability in the mold and under vaccuum
- Useable in Poyester and Urethane Resin Systems
- Available Globally



M 8635 Continuous Filament Mat

Laminate Thickness	**0.102 inches**	**2.6mm**
Wt/ % Glass in Final Laminate 27%		
Tensile - 0 degrees		
Strength	9.5 10^3 psi	65.5MPa
Modulus	1.0 10^6 psi	6.9 GPa
Flexure - 0 degrees		
Strength	23.3 10^3 psi	160.6MPa
Modulus	1.1 10^6 psi	7.6 GPa
Flexure - 90 degrees		
Strength	27.3 10^3 psi	188.2MPa
Modulus	1.1 10^6 psi	7.6 GPa

WET THROUGH/POROSITY

Owens Corning M8635 continuous filament mat offers little resistance to resin flow to allow for easy and complete resin impregnation of parts made using a vacuum infusion process.

RAPID INFUSION REDUCES PART CYCLE TIMES AND INCREASES MOLD TURNOVER

M8635 was specifically designed for infusion molding and has up to 25% higher infusion rates compared to general use CFM products. It provides significantly higher infusion rates compared to chopped strand mat products.

PROVIDES EXCELLENT MECHANICAL REINFORCEMENT

With continuous Fibers randomly dispersed in multiple layers, M8635 provides excellent mechanical reinforcement and alleviates concerns in using organic materials in "below the waterline" applications.

EXCELLENT HANDLING PROPERTIES

M8635 continuous filament mat can be unrolled, cut and conveyed to the mold without losing its integrity.

CONSISTENCY

M8635 continuous filament mat can provide the uniform weight and strand integrity customers desire. And in the end-use application, this mat can provide uniform mechanical properties throughout the vacuum infusion molded part.

AVAILABLE STANDARD PRODUCTS

A. Available Standard Weights * - Grams per square meter (Ounces per Square Foot)

300(1.0), 450 (1.5)., 600(2.0), 750 (2.5). and 900(3.0)

B. Available Standard Trimmed Widths * cm (in)

106.7(42), 121.9(48), 127(50), 129.5(51), 139.7(55), 172.7(68), and 182.9(72)

M 8635 Continuous Filament Mat

PRODUCT DATA

PRODUCT ACCEPTANCE LIMITS AND TEST METHODS

A. Weight (values stated are grams per square foot (12" x 12")

Weight Per Square Foot (Ounces)	Nominal Individual (Grams)	Tolerance (Grams)	OC Test Method
1.00	28.4	+/- 4.3	W-01Fc
1.50	42.5	+/- 6.4	
2.00	56.7	+/- 8.5	
2.50	70.9	+/-10.6	
3.00	85.1	+/-12.8	

B. Edge Weight*

Weight Per Square Foot (Ounces)	Nominal Individual (Grams)	Tolerance (Grams)	OC Test Method
1.00	2.4	+/- 0.7	W-01Fg-T
1.50	3.5	+/- 1.1	
2.00	4.7	+/- 1.4	
2.50	5.9	+/- 1.8	
3.00	7.1	+/- 2.1	

*Values stated are grams per 1" x 12" sample.

C. Ignition Loss %

Weight Per Square Foot (Ounces)	Nominal	Tolerance	OC Test Method
All	2.50	+/- 1.25	W-05Ec

D. Tensile (values stated are based on 12" x 12" test specimens)

Weight Per Square Foot (Ounces)	Minimum Individual	Maximum Individual	OC Test Method
1.00	5	None	S-01AG
1.50	16	None	
2.00	25	None	
2.50	31	None	
3.00	38	None	

M 8635 Continuous Filament Mat

E. Width

Weight Per Square Foot (Ounces)	Nominal (Inches)	Tolerance (Inches)	OC Test Method
All	As specified on the order	+/- 1/8	D-03Aa

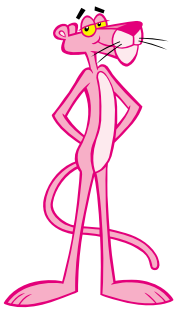
Packaging

A. Rolls
The rolls are individually wrapped in polyethylene.

B. Palletized Rolls
The rolls are multiple packed, twelve (individual or common) rolls for widths less than or equal to 42" or six (individual or common) rolls for wider widths, on a 66" x 44" varying height pallet.

Storage Conditions

Unless otherwise specified, it is recommended to store glass fiber products in a cool, dry area. Temperature should not exceed 35 degrees C (95 degrees F) and the relative humidity should be kept below 75%. Glass fiber products must remain in their original packaging material until just prior to use.



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Lantor Finishmat® D7760/80

Lantor Finishmat®
D7760/80

Technical data

		D7760	D7780
Weight	g/m²	60	80
Thickness	mm	0,30*	0,40*
Roll length	m	100	100
Roll width	m	1,1	1,1
Resin uptake	kg/m²	~400*	~550*
Binder		NO binder**	No binder**
Fibre		Polycralic	Polycralic
Elongation	%	100	100

* depending on process pressure
** mechanically bonded (needled veil)

Lantor Finishmat® D77 grades provide an excellent surface finish for products made in closed mould processes

Lantor Finishmat® D7760/80
- Excellent surface finish
- Reduction of process cycle time
- Gelcoat can be replaced by pigmented resin
- Easy to process
- Becomes translucent in resin
- High elongation

Applications of Lantor Finishmat® D7760/80
- Transportation (parts and panels of cars, trailers, trucks, RV's)
- Marine (hulls, decks and lids of boats and yachts)
- General closed mould applications



The finishing touch!

- Excellent surface finish
- Fibre print blocker
- Reduce process cycle time
- Cost efficient

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LANTOR nl Composites

LANTOR nl Composites

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3A COMPOSITES

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Excellence in Core Solutions

AIREX® foams
- AIREX® C70
- AIREX® C71
- AIREX® T90
- AIREX® T92
- AIREX® R63
- AIREX® R82
- AIREX® C51
- AIREX® PXc
- AIREX® PXw
- Production process

BALTEK® balsa
- BALTEK® SB
- Balsa production
- FSC-certified responsible forestry management

Lantor Mats
- Bulker Mats
- Finishmat®

Finishing options
Sandwich technology
All about cores

Finishmat

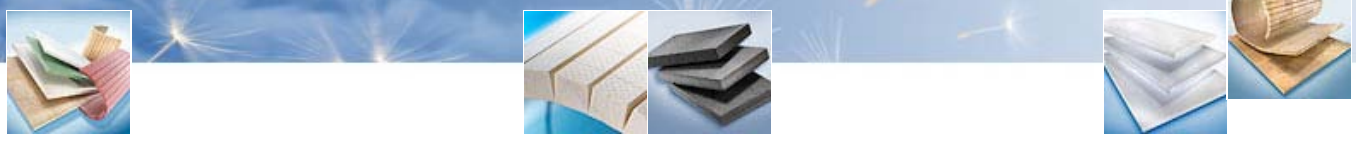
- Finishmat® D7760 is a polyacrylic non-woven veil that produces an excellent surface finish for all products made in closed molding processes.
- The fibers have 100% elongation and do not contain any binder. This allows the material to become translucent in resin and eliminates most glass fiber print at the laminate surface.
- Additional finishing steps can be eliminated saving time and money. The use of Finishmat® even allows parts that require high-quality cosmetics to be produced without a gelcoat.
- Finishmat® is compatible with all types of resins and can be used in most manufacturing process, including vacuum infusion, RTM, filament winding, press lamination, and pultrusion.
- Finishmat® has a fabric weight of 1.77 oz/yd2 (60 g/m2) and is supplied in rolls 44 ft. (1.1 m) wide and 329 ft. (100 m) long. It will absorb up to 1.32 oz/ft2 (400 g/m2) of resin depending on process pressure.

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References

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Divinycell® H Technical Data

Divinycell H has been widely used over many years in virtually every application area where sandwich composites are employed including the marine (leisure, military and commercial), land transportation, wind energy, civil engineering/ infrastructure and general industrial markets. In its application range Divinycell H has the highest strength to density ratio. It exhibits at both ambient and elevated temperatures impressive compressive strength and shear properties. In addition the ductile qualities of Divinycell H make it ideal for applications subject to fatigue, slamming or impact loads.

Other key features of Divinycell H include consistent high quality, excellent adhesion/peel strength, excellent chemical resistance, low water absorption and good thermal/acoustic insulation. Divinycell H is compatible with virtually all commonly used resin systems (polyester, vinyl ester and epoxy) including those with high styrene contents. Its good temperature performance with high residual strength and good dimensional stability, makes Divinycell H ideal for hand laminating, vacuum bagging, RTM (resin transfer molding) or vacuum infusion.

Technical Data for Divinycell H Grade

Property	Method	Unit	H35	H45	H60	H80	H100	H130	H160	H200	H250
Nominal Density [1]	ISO 845	kg/m^3	38	48	60	80	100	130	160	200	250
		lb/ft^3	2.4	3.0	3.8	5.0	6.3	8.1	10.0	12.5	15.6
Compressive Strength [2]	ASTM D 1621	MPa	0.45	0.6	0.9	1.4	2.0	3.0	3.4	4.8	6.2
		psi	65	87	130	203	290	435	493	696	899
Compressive Modulus [2]	ASTM D1621	MPa	40	50	70	90	135	170	200	240	300
		psi	5,800	7,250	10,150	13,050	19,575	24,650	29,000	34,800	43,500
Tensile Strength [2]	ASTM D 1623	MPa	1.0	1.4	1.8	2.5	3.5	4.8	5.4	7.1	9.2
		psi	145	203	261	363	508	696	783	1,030	1,334
Tensile Modulus [2]	ASTM D 1623	MPa	49	55	75	95	130	175	205	250	320
		psi	7,105	7,975	10,875	13,775	18,850	25,375	29,730	36,250	46,400
Shear Strength	ASTM C 273	MPa	0.4	0.56	0.76	1.15	1.6	2.2	2.6	3.5	4.5
		psi	58	81	110	167	232	319	377	508	653
Shear Modulus	ASTM C 273	MPa	12	15	20	27	35	50	73	85	104
		psi	1,740	2,175	2,900	3,915	5,075	7,250	10,590	12,325	15,080
Shear Strain	ASTM C 273	%	9	12	20	30	40	40	40	40	40

1) Typical density variation ± 10%.

2) Perpendicular to the plane. All values measured at +23°C (73.4°F).

Continuous operating temperature is –200°C to +70°C (–325°F to +160°F). The foam can be used in sandwich structures, for outdoor exposure, with external skin temperatures up to +85°C (+185°F). For optimal design of applications used in high operating temperatures in combination with continuous load, please contact DIAB Technical Services for detailed design instructions. Normally Divinycell H can be processed at up to +90°C (+194°F) with minor dimensional changes. Maximum processing temperature is dependent on time, pressure and process conditions. Therefore users are advised to contact DIAB Technical Services to confirm that Divinycell H is compatible with their particular processing parameters.
Coefficient of linear expansion: approx. 22.2 x 10^{-6}/°F (40 x 10^{-6}/°C)

This data sheet may be subject to revision and changes due to development and changes of the material. The data is derived from tests and experience. The data is average data and should be treated as such. Calculations should be verified by actual tests. The data is furnished without liability for the company and does not constitute a warranty or representation in respect of the material or its use. The company reserves the right to release new data sheets in replacement.

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Corecell™ M FOAM

The Marine Foam

- **Replacement for PVC cores**
- **High shear strength combined with low density**
- **High temperature processing (prepreg compatible)**
- **High elongation for toughness**
- **Suitable for all composite processes including prepreg**
- **Benefits from GL, DNV, RINA and ABS certification**

Introduction

Corecell M-Foam is the newest addition to the Corecell range and shares the benefits of SAN chemistry common to all Corecell products.

Environmental stability – High tolerance for heat and chemical exposure
Built in toughness – High ductility and damage tolerance compared to cross-linked PVC and Balsa
Fine cell size – Resin absorption is very low, saving both weight and cost
Superior uniformity – Low density variation
Eliminating outgassing – Corecell eliminates the problems of foam outgassing
Compatibility – Suitable for use with all polyester, vinylester and epoxy resins
No inhibition - Corecell does not inhibit any epoxy resin curing mechanisms
Handling – Tough and easy to machine

Corecell M-Foam has been developed to deliver one product for all Marine applications. It provides a combination of high shear strength with low density, high elongation, high temperature resistance and low resin uptake. M-Foam is the perfect choice whether your application is slamming area or superstructure, hull or deck, using hand lamination, infusion or prepreg.

If looking for reliable processing, M-Foam delivers through the benefits recognised in all Corecell products of fine cell size and unique knife-cuts giving low resin uptake in infusion processes. For prepreg, M-Foam offers high temperature resistance to allow shorter cure cycles and the confidence to process without fear of inhibition of prepreg catalysis. Where static properties are important, M-Foam delivers high shear strength at a low density. Where dynamic performance is crucial, the high elongation delivers higher useful properties and the toughness to give impact resistance and superior fatigue performance.

Corecell M-Foam is available in resin infusion format and is compatible with polyester, vinylester and epoxy resin systems. The low resin absorption characteristics of Corecell and it's unique knife cut formats deliver higher performing infusions, low resin cost and low weight. Gurit's global technical team have 10 years experience in resin infusion, hand lamination and prepreg processing and offer on-site support and structural engineering for Corecell customers. This combination makes Corecell a key part of a reliable package.

Type	Test Method	Units	M60	M80	M100	M130	M200
Nominal Density		kg/m³	65	85	107.5	140	200
		lb/ft³	4.1	5.3	6.7	8.7	12.5
Density Range		kg/m³	61-69	81-89	100-115	130-150	185-215
		lb/ft³	3.8-4.3	5.1-5.6	6.2-7.2	8.1-9.4	11.5-13.4
Compression Strength	ASTM D1621	MPa	0.55	1.02	1.55	2.31	4.40
		psi	80	148	225	336	638
Compressive Modulus	ASTM D1621-1973	MPa	45	71	107	170	317
		psi	6480	10340	15570	24670	45977
	ASTM D1621-2004	MPa	31	52	76	111	210
		psi	4530	7610	11080	16100	30458
Shear Strength	ASTM C273	MPa	0.68	1.09	1.45	1.98	2.95
		psi	98	158	211	287	428
Shear Modulus	ASTM C273	MPa	20	29	41	59	98
		psi	2900	4240	5920	8600	14214
Shear Elongation at break	ASTM C273	%	53%	58%	52%	43%	20%
Tensile Strength	ASTM D1623	MPa	0.81	1.62	2.11	2.85	4.29
		psi	118	234	306	414	622
Tensile Modulus	ASTM D1623	MPa	44	72	109	176	334
		psi	6440	10420	15880	25510	48443
Thermal Conductivity	ASTM C518	W/mK	0.03	0.04	0.04	0.04	0.04
HDT	DIN 53424	°C	110	110	110	110	110
		°F	230	230	230	230	230

Please Note:

Data quoted is average data at each product s nominal density, and is derived from our regular testing of production materials.

Statistically derived minimum value data, satisfying the design requirements of various classification societies, is available on request.

Notice

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PRO-SET®

LAMINATING EPOXY

ADHESIVES

PROCESS EQUIPMENT

Technical Data

117LV Resin/237 Hardener

Laminating Epoxy

This combination is intended specifically for resin infusion and closed mold processes. It is not appropriate for open molding.

The 117LV/237 Epoxy system is formulated for laminating synthetic composite structures using closed mold processes. The 117LV/237 mixture will provide a working time of approximately 260 minutes at 72° F. A typical laminate will be gelled in approximately 7-8 hrs. at 72° F.

MIXING

Combine PRO-SET 117LV Infusion Resin with PRO-SET 237 Hardener following the ratios by weight or volume shown in the table. Stir the mixture thoroughly and transfer to feed containers connected to the resin distribution system.

CURING

PRO-SET 117LV/237 maintains excellent low viscosity characteristics providing a good flow rate until gel takes place and the mixture cures to a brittle "B" stage. Elevated temperature post cure of 125°F to 180°F **is required** for mixture to reach final cure.

We recommend building sample panels using proposed materials and procedures to understand working and curing characteristics under your shop conditions.

HANDLING CHARACTERISTICS *(Not for specification purposes)*

Property	**Mixed Resin/Hardener**
Density	9.0 lb/gal
Viscosity @ 72°F (ASTM D-2393-80)	360 cps

Mix Ratio (117LV Resin:237 Hardener)	**Target**	**Acceptable Range**
by weight	100:30	100:33.9 to 100:27.1
by volume	100:36	100:40.2 to 100:32.2

Pot Life (ASTM D-2427-71)	**100g**	**500g**
@72°F	281 min	139 min
@80°F	190 min	124 min
@88°F	105 min	75 min

Pro-Set Inc.
P.O. Box 656
Bay City, MI 48707 USA
888-377-6738
prosetepoxy.com

PRO-SET is a registered trademark of Pro-Set Inc.

ISO 9001:2000 certified

August 2005

PRO-SET®

PHYSICAL PROPERTIES

117LV Resin/237 Hardener

Physical Property	Test Method	Cure Schedule				
		Room Temp. Cure	RT* × 15hr + 125°F × 16hr	RT × 15hr + 140°F × 8hr	RT × 15hr + 140°F × 16hr	RT × 15hr + 180°F × 8hr
Hardness (Shore D)	ASTM D-2240	Post Cure Required	85	85	85	85
Compression Yield (psi)	ASTM D-695		15,498	15,865	15,431	15,349
Tensile Strength (psi)	ASTM D-638		10,047	10,015	10,186	10,474
Tensile Elongation (%)	ASTM D-638		3.9	4.3	4.8	5.9
Tensile Modulus (psi)	ASTM D-638		4.61E+05	5.20E+05	4.99E+05	4.89E+05
Flexural Strength (psi)	ASTM D-790		18,837	17,641	18,625	18,423
Flexural Modulus (psi)	ASTM D-790		5.22E+05	5.10E+05	5.06E+05	4.80E+05
Heat Deflection (°F)	ASTM D-648		146	154	164	184
Glass Transition Temperature (°F)**			151	158	168	186
Ultimate Tg–second heat (°F)**			197	197	197	197
Izod Impact, notched (ft-lb/in)	ASTM D-256		0.86	1.26	1.19	0.86

* Room Temperature (70°F–75°F)
** Determined using a Differential Scanning Calorimeter (DSC). Value reported is the onset of the glass transition.
Typical values; not to be construed as specification.
Test specimens were neat epoxy (without fiber reinforcement).

January 2001

CCP COOK COMPOSITES & POLYMERS

EPOVIA™ Vinyl Ester Resin

EPOVIA™ RF1001L-00
EPOXY VINYL ESTER INFUSION RESIN
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DESCRIPTION:

EPOVIA™ RF1001L-00 is an unpromoted, Bisphenol-A based vinyl ester resin containing styrene monomer. **EPOVIA™ RF1001L-00** is formulated for building reinforced plastic parts using closed molding processes and specifically infusion processes such as vacuum bagging, SCRIMP® and resin injection.

EPOVIA™ RF1001L-00 can be used in infusion applications that specify Derakane® 411, Hetron® 922, Dion® 9100, Vipel® F010 and other equivalent Bisphenol-A based vinyl ester resins. **EPOVIA™ RF1001L-00** is suitable for use in a wide range of end-use applications including:

- Corrosion resistant storage tanks for many industries, process pipes, flanges and fittings
- Infrastructure pipe construction
- Fume and vapor ducting
- Load-bearing, structural construction members
- Automotive structural or heat exposed parts

Please refer to the EPOVIA™ Corrosion Guide for RF1001 for detailed information on specific service conditions.

FEATURES AND BENEFITS:

- Low viscosity for easy flow through glass fiber fabrics and cores
- Excellent heat resistance allows use at elevated service temperatures.
- Excellent corrosion resistance to large number of chemicals including acids, alkalis, and solvents. (Note: Please refer to the **EPOVIA™ Corrosion Guide** for **RF1001** for detailed information on specific service conditions.)
- Low shrinkage for good dimensional stability for accurate design tolerances.
- Superior mechanical strength allows for larger safety factors in high stress applications.
- Unpromoted formulation allows for customization of fast and slow gel times for small or large parts.

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www.ccponline.com

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LIQUID PROPERTIES (77ºF, 25ºC):

Liquid properties of **EPOVIA™ RF1001L-00** are shown below. These values may or may not be manufacturing control criteria. They are listed for a reference guide only. Particular batches will not conform exactly to the numbers listed because storage conditions, temperature changes, age, testing equipment (type and procedure) can have a significant effect on the results. Products with properties outside of these readings can perform acceptably. Final suitability of this product should be determined by the fabricator in the end use performance.

Test	Value
Viscosity	100 cps
Weight Per Gallon	8.7 lbs
Specific Gravity @ 25°C	1.04

Notes:

1. Brookfield, LV #2 spindle @ 60 rpm.

PHYSICAL PROPERTIES:

The physical properties of **EPOVIA™ RF1001L-00** are shown below. Properties are shown for both a neat resin casting and for a glass fiber reinforced laminate. These are typical values and are provided for reference only.

Note: The physical properties of thermoset resins evolve as the resin cures. The properties given below are for well cured castings and laminates. Resin and laminates at different stages of cure will have varying properties.

Test	Test Method	Neat Resin Casting[1]	Laminate[2]
Tensile Strength	ASTM D638	12,000 psi	18,000 psi
Tensile Modulus		540,000 psi	1,300,000 psi
Tensile Elongation		5.5%	1.8%
Flexural Strength	ASTM D790	22,000	29,000 psi
Flexural Modulus		500,000psi	1,200,000 psi
Heat Distortion Point at 264 psi	ASTM D648	108°C/226°F	--
Barcol Hardness		40	52
Glass Content	ASTM D2584	--	See Note 2.

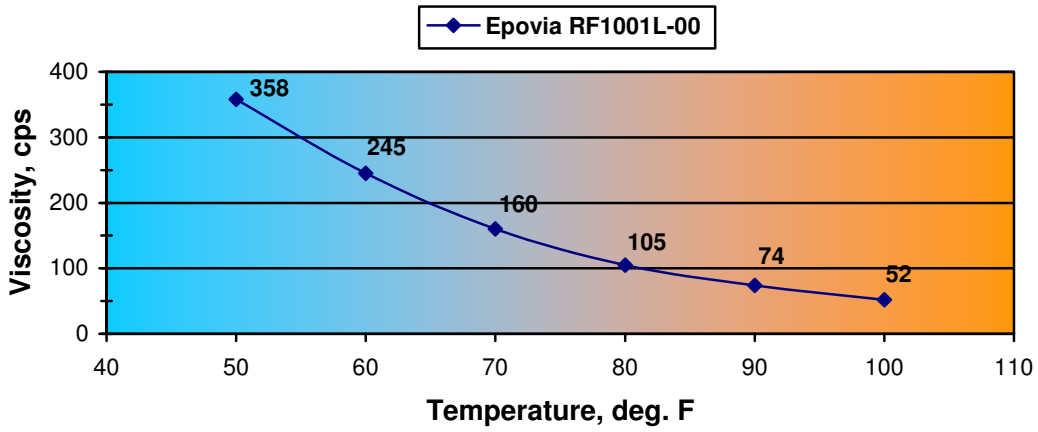
NOTES:

1. Neat Resin Casting – Post cured for 2 hours at 80ºC for followed by 2 hours at 120ºC.
2. Laminate - Laminate construction is as follows: 1 surface layer (10% glass), 1 chopped strand mat (25% glass), 1 chopped strand plus roving and reinforcement (35% glass)
3. Reference Cray Valley Korea

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APPLICATION:

EPOVIA™ RF1001L-00 is formulated with a low viscosity for thorough wet out of reinforcing materials and rapid fill times. To fully realize the benefit of **EPOVIA™ RF1001L-00's** low viscosity, temperature control is recommended. Resin viscosity is affected by temperature with the resin being higher in viscosity at cooler temperatures and lower at warmer temperatures. The affect of temperature on viscosity is represented below.



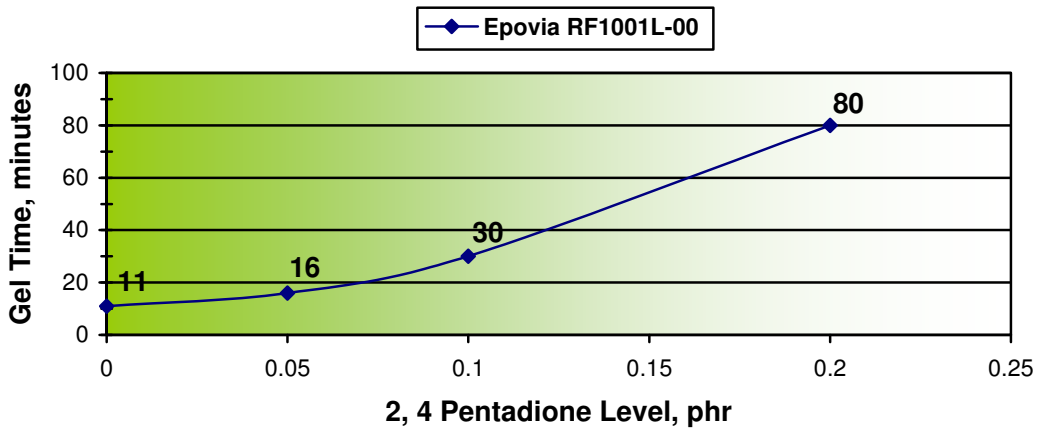
EPOVIA™ RF1001L-00 is unpromoted to allow for customization of fast and slow gel times for small or large parts. Sample promotion formulations for fast, medium, slow and extended gel times are shown below. The samples formulations are provided as a guideline only. CCP recommends that gel time be checked in the customer's plant because age, temperature, humidity, promoter levels and peroxide age and type will produce varied gel times.

Gel Time	Fast	Medium	Slow	Extended
	11 min.	**16 min.**	**30 min.**	**80 min.**
Promoter: 12% COBALT	0.15 phr	0.15 phr	0.15 phr	0.15 phr
Co-promoter: DMA	0.05 phr	0.05 phr	0.05 phr	0.05 phr
Inhibitor: 2,4 pentadione	none	0.05 phr	0.10 phr	0.20 phr

Notes:

1. Method CCP-22-TAS-TM-515.2 - 1.25% Syrgis® MEKP-925H at 77ºF (25ºC)

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www.ccponline.com



EPOVIA™ RF1001L-00 is quality control tested using Syrgis® MEKP-925H. Other MEKP catalysts such as Arkema Luperox® DHD-9, Syrgis NOROX® MEKP-925, and Chemtura HP-90 are expected to yield similar performance. Syrgis NOROX® MEKP-9 and NOROX® MEKP-9H, Akzo Nobel CADOX L-50a and CADOX D-50 may also be used, but gel and cure times may vary.

The catalyst level should not exceed 2.4% nor fall below 0.9% for proper cure. The recommended range is 1.5% at 25°C or 77°F depending on material and room temperature, humidity, air movement, and catalyst concentration.

This product should not be used when temperature conditions are below 18°C (64°F), as significantly longer gel, poor flow, and poor cure should be expected.

RELATED PRODUCTS:

- **EPOVIA™ RF1001L-15 –** Pre-promoted infusion resin for small parts.
- **EPOVIA™ RF1001L-56** – Pre-promoted infusion resin with extended gel time and controlled exotherm for large/thick parts.
- **EPOVIA™ RF1001DMV** – Unpromoted, medium viscosity version (400 cps) for non-infusion applications.

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CAUTION:

Do not add any material, other than the recommended promoters, co-promoters, inhibitors and methyl ethyl ketone peroxide to this product without the advice of a representative of the Cook Composites and Polymers Company.

STORAGE:

EPOVIA™ RF1001L-00 has a usage life of 6 months from date of shipment from CCP when stored at 73°F or below in a closed, factory-sealed, opaque container, and out of direct sunlight. The usage life is cut in half for every 20°F over 73°F.

SHIPPING:

Shipment is made in standard 55-gallon, closed head drums or tank wagons.

DATA SHEETS/MSDS:

CCP data sheets and MSDS's are available in printable format at www.ccponline.com.

RJP 04/09

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COOK COMPOSITES AND POLYMERS CO.

WARRANTIES, DISCLAIMERS, AND LIMITATION OF LIABILITY (Rev. 03/09)

Seller warrants that: (i) Buyer shall obtain good title to the product sold hereunder, (ii) at Shipment such product shall conform to Seller's specifications; and (iii) the sale or use of such product will not infringe the claims of any U.S. patent covering the product itself, but Seller does not warrant against infringement which might arise by the use of said product in any combination with other products or arising in the operation of any process. **SELLER MAKES NO OTHER WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, INCLUDING WITHOUT LIMITATION ANY WARRANTY OF MERCHANTABILITY OR FITNESS FOR ANY PARTICULAR PURPOSE, EVEN IF THAT PURPOSE IS KNOWN TO SELLER, ANY APPLICATION INFORMATION OR ASSISTANCE WHICH SELLER MAY FURNISH TO BUYER IS GRATUITOUS AND SHALL IN NO WAY BE DEEMED PART OF THE SALE OF PRODUCT HEREUNDER OR A WARRANTY OF THE RESULTS OBTAINED THROUGH THE USE OF SUCH PRODUCT.**

Without limiting the generality of the foregoing, if any product fails to meet warranties mentioned above, seller shall at seller's option either replace the nonconforming product at no cost to Buyer or refund the Buyer the purchase price thereof. The foregoing is Buyer's sole and exclusive remedy for failure of Seller to deliver or supply product that meets the foregoing warranties. Seller's liability with respect to this contract and the product purchased under it shall not exceed the purchase price of the portion of such product as to which such liability arises. Seller shall not be liable for any injury, loss or damage, resulting from the handling or use of the product shipped hereunder whether in the manufacturing process or otherwise. In no event shall Seller be liable for special, incidental or consequential damages, including without limitations loss of profits, capital or business opportunity, downtime costs, or claims of customers or employees of Buyer. Failure to give Seller notice of any claim within thirty (30) days of Shipment of the product concerned shall constitute a waiver of such claim by Buyer, Any product credit received by Buyer hereunder, if not used, shall automatically expire one (1) year from the date the credit was granted. Notwithstanding any applicable statute of limitations to the contrary, any action by Buyer in relation to a claim hereunder must be instituted no later than two (2) years after the occurrence of the event upon which the claim is based. All the foregoing limitations shall apply irrespective of whether Buyer's claim is based upon breach of contract, breach of warranty, negligence, strict liability, or any other legal theory.

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COMPOSITES SAFETY INFORMATION

(January 2008)

All sales of products manufactured by Cook Composites and Polymers Co. (CCP), and described herein, are made solely on condition that CCP's customers comply with applicable health and safety laws, regulations and orders relating to the handling of our products in the workplace. Before using, read the following information, and both the product label, and Material Safety Data Sheet pertaining to each product.

Most products contain styrene. Styrene can cause eye, skin and respiratory tract irritation. Avoid contact with eyes, skin and clothing. Impermeable gloves, safety eyewear and protective clothing should be worn during use to avoid skin and eye contact. Wash thoroughly after use.

Styrene is a solvent and may be harmful if inhaled. Reports have associated repeated and prolonged occupational overexposure to solvents with permanent brain and nervous system damage. Extended exposure to styrene at concentrations above the recommended exposure limits may cause central nervous system depression causing dizziness, headaches or nausea and, if overexposure is continued indefinitely, loss of consciousness, liver and kidney damage.

Do not ingest or breathe vapor, spray mists or dusts caused by applying, sanding, grinding and sawing products. Wear an appropriate NIOSH/MSHA approved and properly fitted respirator during application and use of these products until vapors, mists and dusts are exhausted, unless air monitoring demonstrates vapors, mists and dusts are below applicable exposure limits. Follow respirator manufacturer's directions for respirator use.

The International Agency for Research on Cancer (IARC) reclassified styrene as Group 2B, "possibly carcinogenic to humans." This revised classification was not based on new health data relating to either humans or animals, but on a change in the IARC classification system. The Styrene Information and Research Center does not agree with the reclassification and published the following statement: Recently published studies tracing 50,000 workers exposed to high occupational levels of styrene over a period of 45 years showed no association between styrene and cancer, no increase in cancer among styrene workers (as opposed to the average among all workers), and no increase in mortality related to styrene.

Styrene is classified by OSHA and the Department of Transportation as a flammable liquid. Flammable products should be kept away from heat, sparks, and flame. Lighting and other electrical systems in the work place should be vapor-proof and protected from breakage.

Vapors from styrene may cause flash fire. Styrene vapors are heavier than air and may concentrate in the lower levels of molds and the work area. General clean air dilution or local exhaust ventilation should be provided in volume and pattern to keep vapors well below the lower explosion limit and all air contaminants (vapor, mists and dusts) below the current permissible exposure limits in the mixing, application, curing and repair areas.

Some products may contain additional hazardous ingredients. To determine the hazardous ingredients present, their applicable exposure limits and other safety information, read the Material Safety Data Sheet for each product (identified by product number) before using. If unavailable, these can be obtained, free of charge, from your CCP representative or from: CCP, P.O. Box 419389, Kansas City, MO 64141-6389; 816-391-6053.

FIRST AID: In case of eye contact, flush immediately with plenty of water for at least 15 minutes and get medical attention; for skin, wash thoroughly with soap and water. If affected by inhalation of vapors or spray mist, remove to fresh air. If swallowed, get medical attention.

Those products have at least two components that must be mixed before use. Any mixture of components will have hazards of all components. Before opening the packages read all warning labels. Observe all precautions.

Keep containers closed when not in use. In case of spillage, absorb with inert material and dispose of in accordance with applicable regulations. Emptied containers may retain hazardous residue. Do not cut, puncture or weld on or near these containers. Follow container label warnings until containers are thoroughly cleaned or destroyed.

FOR INDUSTRIAL USE AND PROFESSIONAL APPLICATION ONLY. KEEP OUT OF REACH OF CHILDREN.

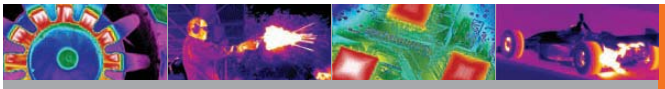
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Appendix C
AEWC Test Equipment and Instrumentation

FLIR™
The Global Leader in Infrared Cameras

NEW! FLIR SC620

R&D INFRARED CAMERA SYSTEM



The SC620 is an affordable research camera with superior thermal and visual image quality, spot size resolution, and temperature measurement accuracy. An advanced feature set includes a built-in digital camera, voice annotation, laser target locator, visual illuminator, and much more.



- Rugged, Ergonomic Features
- Uncooled 640×480 IR Detector Array
- Temperature Range: –40°C to 500°C
- Thermal Sensitivity ≤55mK
- Full Radiometric Real-time Video to PC
- Built-in 3.2 Mpixel visual camera
- 5.6˝ Widescreen On-camera LCD
- Text and Voice Annotation

Features both thermal and visual camera capabilities – at the touch of a button!

High Sensitivity

The SC620 provides exceptional value in thermographic studies and temperature measurements. Its high-definition 640 X 480 infrared detector features 0.05°C sensitivity and ±2°C (3.6°F) accuracy. The result is outstanding resolution and image quality for precise readings on small objects at extended distances.

Flexible Image Integration

A 3.2 megapixel digital camera is an integral part of the SC620, supplying picture-on-picture flexibility with the corresponding thermographic image. The visual camera has a matching Field Of View (FOV) lens, so IR and visual images correlate over various distances. Infrared and visual images can also be stored in standard JPEG formats for easy data presentation.

Versatile Image Capture

In addition to an on-camera LCD screen, the SC620 supplies a composite video output in NTSC or PAL format. Thermal and visual images can also be stored on high capacity (1GB) SD-cards in JPEG format, along with the associated 14-bit temperature measurement data. Its FireWire interface can transfer 14-bit radiometric directly to a PC. In addition, a USB port allows the streaming of MPEG-4 non-radiometric video sequences to the PC, as well as image transfers with measurement data and annotations.

Text and Voice Annotation

Text comments for each image can be entered manually or preloaded from a PC. Furthermore, a user can record 30 seconds of digital voice and embed it with each IR image. These annotation features eliminate the need to keep separate notes to describe the target object, its location, and associated conditions.

Increased Productivity

The SC620 was designed with convenience and productivity in mind. Its multi-angle handle has an integrated joystick and buttons that allow fast point-and-shoot operation. They include features such as auto-focus, freeze-frame, and image storage. The tiltable viewfinder presents the user with high-resolution color imagery. Auto-focus facilitates image capture in hard-to-focus situations, while manual focus provides greater flexibility. A target illuminator lamp ensures good visual reference images in low lighting conditions. All these features and functions help shorten the learning curve, allowing new users to quickly become productive.

Safety Matters

The SC620's large target-distance to spot-size ratio allows users to make accurate measurements swiftly and safely when conducting IR studies in dangerous environments. Furthermore, the camera's laser locator helps associate a spot on the IR image with the exact location of the target object. This greatly enhances user safety by eliminating the tendency to use finger pointing to identify target objects in hazardous areas. An IrDA interface allows wireless communications to remote locations, so users can be positioned outside hazardous areas.

Rugged, Ergonomic Design

The magnesium housing of the SC620 is designed for rugged portability and ergonomic efficiency. It meets the IP54 standard for protection of internal parts from shock, vibration, dust and water-splash. This is accomplished within a package that weighs only 1.7kg (3.8lb), including the rechargeable battery. Users can comfortably carry the SC620 for several hours a day.

Three Hours of Run Time

The rechargeable battery provides up to three hours of operation when fully charged. The SC620 comes with an intelligent charging station capable of conditioning and charging two batteries simultaneously. A user can also plug the camera into an AC outlet or optional 12V cable and charge the battery inside the unit.

Optional Research Package

The optional SC620 Research Package consists of the SC620 camera and the ThermoVision ExaminIR analysis software. FLIR's ThermoVision ExaminIR Software seamlessly stores, retrieves, and analyzes IR images and temperature data directly from the SC620 camera, allowing in depth and precise evaluation of thermal performance. This powerful Windows®-based package for R&D professionals is easy to use for both static and real-time image analysis. It includes temperature display and analysis functions such as isotherms, line profiles, area histograms, and much more. Its high-speed data acquisition capabilities add another level of power and flexibility to thermal imaging and temperature measurements.

Infrared Certification Training and Support

In addition to worldwide service and support, FLIR Systems offers Thermographer certification classes at its state-of-the art facilities near Boston, Massachusetts. The FLIR Systems Infrared Training Center (ITC) is the Global leader in IR Thermography Training.

FLIR SC620 Technical Specifications

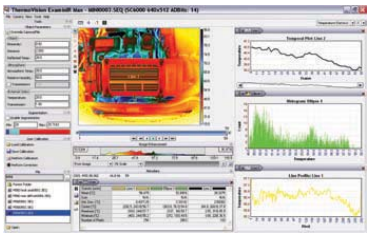
Imaging Performance	
Thermal	
Field of view/min focus distance	24° × 18° / 0.3m
Spatial resolution (IFOV)	0.65 mrad
Thermal sensitivity @ 50/60Hz	55mK at 30°C
Electronic Zoom	1–8× continuous, including pan
Focus	Automatic or manual
Digital image enhancement	Normal and enhanced
Detector type	Focal plane array (FPA) uncooled microbolometer; 640 × 480 pixels
Spectral range	7.5 to 13µm
Visual	
Built-in digital video	3.2 Mpixel, full color / built-in Target Illuminator / exchangeable lens
Standard lens performance	f=8mm / FOV 32°
Image Presentation	
Viewfinder	Built-in, tiltable, high-resolution color viewfinder (800 × 480 pixels)
External display	Built-in 5.6˝ LCD (1024 × 600 pixels)
Video output	RS170 EIA/NTSC or CCIR/PAL composite video
Measurement	
Temperature ranges	–40°C to +500°C, in 3 ranges; up to +2000°C, optional (–40°F to 932°F with option to 3,632°F)
Accuracy (% of reading)	±1°C or ±1% of reading (object within +5°C to to 120°C, ambient within +9°C to 35°C); otherwise ±2°C or ±2%.
Measurement modes	3 Spots/Areas (Boxes, Circles), Isotherms (above, below, interval), Delta T
Menu controls	Palettes, load custom palletes, auto adjust (manual/continuous/based on histogram equilazation), image gallery, sequence storage, programmable storage, on-screen live and reference image (PoP)
Emissivity correction	Variable from 0.1 to 1.0 or select from listings in pre-defined material list
Measurement features	Automatic corrections based on user input for reflected ambient temperature, distance, relative humidity, atmospheric transmission, and external optics
Optics transmission correction	Automatic, based on signals from internal sensors
Atmospheric transmission correction	Automatic, based on inputs fpr distance, atmospheric temperature and relative humidity
Reflected ambient temperature correction	Automatic, based on input of reflected temperature
External optics/window correction	Automatic, based on input of optics/window transmission and temperature
Alarm functions	Automatic alarm on any selected measurement function, audible/visible alarm above/below
Image Storage	
Type	Removable SD-card (1GB)
File format – THERMAL	Standard JPEG; 14 bit thermal measurement data included
File format – VISUAL	Standard JPEG inked with corresponding thermal image
Voice annotation of images	30 sec. of digital voice "clip" stored together with the image wired headset
Text annotation of images	Predefined by user and stored with image
Laser LocatIR™	
Classification type	Class 2, Semiconductor AlGaInP Diode Laser: 1 mW/635 nm (red)
Power Source	
Battery type	Li-Ion, rechargeable, field-replaceable
Battery operating time	3 hours continuous operation
Charging system	In camera (AC adapter or 12V from car) or 2 bay intelligent charger
External power operation	AC adapter 110/220 VAC, 50/60Hz or 12V from car (cable with standard plug optional)
Power saving	Automatic shutdown and sleep mode (user-selectable)
Environmental	
Operating temperature range	–15°C to +50°C (5°F to 122°F)
Storage temperature range	–40°C to +70°C (–40°F to 158°F)
Humidity	Operating and storage 10% to 95%, non-condensing
Encapsulation	IP 54 IEC 529
Shock	Operational: 25G, IEC 68-2-29
Vibration	Operational: 2G, IEC 68-2-6
Physical Characteristics	
Weight	1.7kg (3.8 lbs) w/battery
Size	120mm × 145mm × 220mm
Tripod mounting	1/4˝– 20

Camera includes:
Camera with visual and IR lens
Power supply
2 batteries (3 hours operating time on each)
2 bay charging station
QuickReport software
Manual and Quick Reference Card
Headset
Cables

Lenses (optional)	
Automatic lens identification **Field of view/minimum focus distance**	
12° × 9° / 0.9m telelens	
45° × 34° / 0.1m wide angle lens	
Close-up 32 mm × 24 mm / 75 mm	

Interfaces	
1394 Firewire	Fully radiometric 14bit real time image video to PC
USB	Image (thermal and visual), measurement data, voice and text transfer to PC
IrDA	Wireless communication
SD-card (2)	I/O slot; storage slot

NEW!
RUGGED & LIGHTWEIGHT **MAGNESIUM** HOUSING!



ThermoVision ExaminIR example display





FLIR™
The Global Leader in Infrared Cameras

1 800 464 6372
CANADA: 1 800 613 0507
www.infraredresearchcameras.com

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Q-800

Portable Shearography NDT System

Applications

- Non Destructive Testing method for a large variation of different composite materials.
- Reinforced plastics, laminates, honeycomb, foam, wood, metal, Glare etc.
- Approved in the aerospace, automotive wind turbine and other industries

Features

- Fully portable NDT measuring solution
- Detects delaminations, disbonds, kissing bonds, wrinkling, impact damage and many more
- Non-contact and full field - no surface preparation
- Live display - fast results



Portable Q-800 System with 4 laser diodes - Non Destructive Testing, Non-Contact, Full-Field

Introduction

Shearography is a Non Destructive Testing technology that provides fast and accurate information about the inside quality of different materials.

State of the Art Performance

The Q-800 Laser Shearography System is a compact and fully portable NDT measuring solution that can detect defects, delaminations, disbonds, kissing bonds, wrinkling, impact damage and many more. The turn-key optical system is non-contact and full-field and will work on such materials as fiber reinforced plastics, laminates, honeycomb, foam, wood, metal and Glare.

Real-time Inspection

The results are displayed live to the operator allowing an early judgment to be made. Further image processing is also available for export and reporting. Typical inspection times are 10 to 30 seconds and can cover areas from a few mm² up to several m² in one inspection. The Q-800 system consists of a miniaturized shearography sensor with integrated high-resolution CCD and variable computer controlled shear optics. Illumination is provided by an integrated diode laser array and the whole system is controlled from a laptop PC using the new ISTRA 4D software platform.

DANTEC DYNAMICS

Q-800

Product Information

The sensor can be mounted on a tripod or integrated into a fully automatic robotic production inspection system.The system can be operated in daylight conditions using the standard laser diode array.

A Certified Technique

Shearography has been incorporated in ASNT standards since 2006. (SNT-TC1-A and CP-105). ASTM standard (ASTM E2581) defines how to inspect composites with shearography. Laser shearography has been approved by leading suppliers in the aerospace, automotive wind turbine and other industries.

Measurement Principle

The highly sensitive interferometric technique will measure microscopic surface deformations caused by internal flaws when a small loading is applied to the object. This can be done using thermal, pressure, vibration or mechanical excitation.

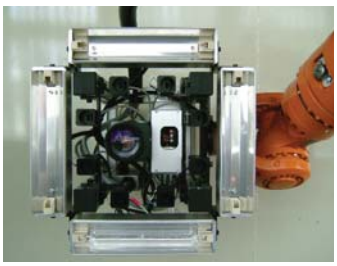
The results are displayed live as the material responds to the excitation and are easily interpreted by the operator.

Additional information

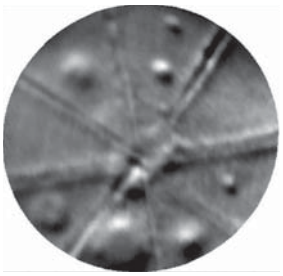
For additional information please contact your Dantec Dynamics representative.



Portable Q-800 System with 2 laser diodes



Q-800 sensor integrated In a robot inspection system



Live results from an inspection showing impact damage and structural information

Technical specifications	
CCD-resolution	1392 x 1040 pixels
Inspection Speed	Typically 300 mm x 300 mm / 20 s
Shear angle	up to 1/20 the field-of-view, fully adjustable (software controlled)
Shear direction	0-180°, fully adjustable (software controlled)
Measuring area	300 mm x 200 mm with 2 laser diode array 700 mm x 700 mm with 4 laser diode array ~ 1,2 m² with 8 laser diode array > 1,2 m² with 5 W external laser (option)
Sensor head dimension	W x H x D = 70 mm x 70 mm x 160 mm
Sensor head weight	1.2 kg incl. zoom lens
Options	
Motorized pan/tilt sensor and zoom lens for remote operation, Vacuum tripod	
Manual and automated excitation systems: Vacuum chamber/ hood; Heating systems; Vibration excitation systems	
Customised inspection solutions	
EN 4179, NAS 410 and ASNT SNT-TC-IA Training Courses	

The specifications in this document are subject to change without notice.

DANTEC DYNAMICS

www.dantecdynamics.com

Partners for progress

Publication No.: PI-Q-800_09_01

Q-810

Portable Shearography NDT System for Field Use

Applications

- In-field use of large area NDT inspections delaminations, disbonds, kissing bonds, wrinkling, impact damage, crushed core and many more.
- Defect detection in composite materials carbon fiber, glass fiber, laminates, honeycomb etc.
- Inspect structural integrity, separation of structural components and bond lines.

Features

- Rapid full-field inspection rate 300 mm x 200 mm every 10 seconds.
- Adaptive seals for usage on highly curved surfaces.
- Operates independent of the local environmental conditions and can be used for production or in-field inspections



Fully integrated Q-810 Pro-line inspection system for production and in-field inspection of large surface areas

Introduction

The portable ***Q-810 Laser Shearography Systems*** are fully integrated NDT systems using laser shearography. The systems are suitable for defect detection in composite materials over large surface areas, in tough field environments.

State of the art NDT Performance

The Q-810 Systems can detect defects such as delaminations, disbonds, kissing bonds, wrinkling, impact damage, crushed core and many more with no surface preparation. and bond lines. The turn-key optical systems are ***non-contact*** and ***full-field*** and will work on such materials as carbon-fiber, glass-fiber, laminates, honeycomb, foam, metal and Glare.

Large Surface Area Coverage

The integrated systems are optimised for large surface area inspections, for example on aircraft fuselages, wings, control surfaces, ship hulls, wind turbine blades and rocket components. The full-field inspection rate is a rapid ***300 mm x 200 mm every 10 seconds***. With adaptive seals the systems can be used on flat as well as highly curved surfaces. The systems operate independently of the local environmental conditions and can be used for production or in-field inspections.

DANTEC DYNAMICS

Q-810

Product Information

Measurement Principle

The highly sensitive interferometric technique will measure microscopic surface deformations caused by internal flaws when a small loading is applied to the object. This can be done using thermal, pressure, vibration or mechanical excitation.

The results are displayed live as the material responds to the excitation and are easily interpreted by the operator. Further image processing is also available for export and reporting.

Fully Integrated system

The Q-810 Systems consist of a vacuum hood with integrated shear optics and a laser diode illumination array which are both ***hermetically sealed*** to protect against dust and debris. The hood has an interchangeable flexible seal adapter and adjustable feet to provide a solid contact to the test object and tight pressure seal. The vacuum hood of the Q-810 provides lock-on and pressure excitation down to 150mbar and an optional heat source can be fitted to provide additional heat excitation.

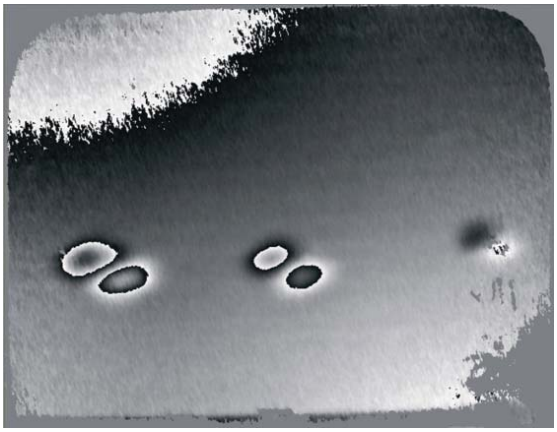
The vacuum hood is connected to a base unit by means of a *standard length* 10 m umbilical cable. The base unit houses the PC, control electronics and vacuum pump with a large monitor and keyboard. The complete system is controlled by the latest ISTRA 4D software platform.



Very user-friendly operation

The complete system can be operated remotely using ***two buttons*** integrated into the handles of the vacuum hood. A ***touch-screen monitor*** can be fitted to the vacuum hood providing complete system control and allowing easy single operator usage.

The design of the hood and seal allows inspection very close to the edges of the component (< 15 mm). While the standard seal adapters already cover a large range of applications, (radii +/- 850 mm) special interchangeable adapters can be provided for specific geometries, such as small radii or corners.



Defects in a composite panel

A Certified Technique

Shearography has been incorporated in ASNT standards since 2006. (SNT-TC1-A, and CP-105). ASTM standard (ASTM E2581) defines how to inspect composites with shearography. Laser shearography has been approved by leading suppliers in the aerospace, automotive wind turbine and other industries.

Eco, Comfort, Pro-line System Variants

The Q-810 range is designed to be used for a large array of applications and also by different user skill levels. Therefore we provide three model variants based on a common system platform. The Eco, Comfort and Pro-line models offer increasing levels of capability, functionality and flexibility and can be matched to the customer requirements.





Technical specifications

Field of view	W x D = 300 mm x 200 mm
Inspection speed	Typically 300 mm x 200 mm / 10 s
Max. pressure difference	150 mbar 50 mbar hold, 100 mbar test
Max. object curvature	Flat to +/- 850 mm radii with standard seal
Vacuum hood dimensions	W x D x H = ca. 430 mm x 280 mm x 315 mm
Vacuum hood weight	~7.5 kg
Length Umbilical cable	Standard 10 m
Laser Classification	**I**

Q-810 Available Options	Eco	Comfort	Pro
BASE CONTROL UNIT			
Sealed robust aluminium case containing all electronics. Mounted on wheels for mobility, filtered cooling air	✓	✓	✓
Built-in electronics, power supply	✓	✓	✓
Industrial Pentium PC, Windows XP	✓	✓	✓
Mouse, Keyboard, DVD-rewriter, network connector	✓	✓	✓
Integrated 17” TFT monitor	✓	✓	✓
Shutter control with interlock circuit	✓	✓	✓
Split electronics rack with storage compartment for hood		✓	✓
Piezo system for Phase stepping		✓	✓
Key interlock for laser illumination	✓	✓	✓
Computer controlled camera functions			✓
Connection for external Q-800 Sensor		O	✓
VACUUM HOOD			
Vacuum Hood with Handles	✓	✓	✓
2 button control system	✓	✓	✓
Single interface connector to electronics	✓	✓	✓
Standard Seal adapter	✓	✓	✓
Curved Seal adapters	O	O	O
10 m umbilical cable	✓	✓	✓
Extension to umbilical cable	O	O	O
Hood mounted monitor		✓	✓
Touch-Screen Option for Hood monitor		✓	✓
Automatic Feet adjustment		✓	✓
Heat excitation device		O	O
High-Resolution Sensor		✓	✓

O- Option

Q-810

Product Information

SOFTWARE			
Adjustable Pressure Control	✓	✓	✓
Live Image Display	✓	✓	✓
Fringe Display (Image subtraction)	✓	✓	✓
Contrast adjustment (Fringe image)	✓	✓	✓
Record function (Fringe Image)	✓	✓	✓
Adjustable laser power		✓	✓
Phase shifting for Fringe image		✓	✓
Real-time phase shifting		✓	✓
Demodulation of phase image		✓	✓
Visualisation of results		✓	✓
Image Filter Options		✓	✓
Improved Fringe Image and Phase image		✓	✓
Graphical functions		✓	✓
Automatic data storage functions		✓	✓
Recordable Measurement Series		✓	✓
Automatic Object calibration			✓
Defect Sizing			✓
Automatic Image optimisation			✓
Defect Annotation			✓
EMC COMPATIBILITY			
EMC approved system to DEF STAN 59-411	O	O	O
TRAINING			
1 Day Training at Dantec Dynamics	✓		
2 Day Installation and Training at customer site		✓	✓
1 Day Application Training at customer site	O	✓	✓
Certified NDT Level 1 / 2 Training to ASNT or EN standards	O	O	O

The specifications in this document are subject to change without notice

O- Option







DANTEC DYNAMICS

www.dantecdynamics.com

Partners for progress

Publication No.: PI-Q-810_09_01

Data Physics Corporation

Solutions to signal processing challenges from people that are driven by them.

QUATTRO

An Ultra-Portable, Cost-effective DSA Engine

The Data Physics Abacus signal analysis engine revolutionized the dynamic test world two years ago with its unparalleled computing power and performance. With over 4000 channels having been delivered since its launch at IMAC XXI, it has brought new dimensions to product reliability and customer confidence. Now Quattro delivers comparable power in a pocket sized package. With 4 inputs, 2 outputs and 1 tachometer channel, it is the complete solution for small channel count applications.

Ultra portable and rugged, it provides USB 2.0 connectivity to a host PC or laptop and is completely bus powered. With realtime analysis capability from DC to 93 kHz (204.8 kHz sample rate) it is an NVH engineer's dream machine. Simply load the software, connect the USB cable between Quattro and the PC and it is ready to begin measurement.

Perfect for many Applications

Quattro provides a powerful and highly mobile backbone for the most demanding applications. 4 inputs and 2 outputs make it ideal for advanced modal testing including MIMO analysis. The easily configurable tachometer input makes difficult machinery diagnostics effortless and with a host of available measurements including synchronous averaging, order tracking, demodulation and a complete rotordynamics toolkit, it is ideally suited for troubleshooting any rotating machinery problem.

Legendary SignalCalc Software Suite

Quattro interfaces to the universally popular SignalCalc software environment. User configurable control and measurement panels, unlimited display layouts and intelligent data management combine to make any PC a powerful and intuitive Dynamic Signal Analyzer.

Record and Analyze Data in any Environment

With its compact size, rugged design and the ability to record data on all channels at a rate of 204.8 ksamples/sec, it can tackle data acquisition in aircraft, in-vehicle and industrial environments with ease and efficiency. Weighing just over a pound, it provides a uniquely mobile yet powerful test platform.









INTERTECHNOLOGY

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Data Physics Corporation

Solutions to signal processing challenges from people that are driven by them.

Hardware Specifications

INPUT



2 to 4 channels
ADC Resolution (Analog AAF): 24 bits
Sample Resolution (Digital AAF): 32 bit floating point
Coupling: AC/DC, Diff., SE, ICP
Anti-alias Filters: 100 dB protection, all ranges
Dynamic Range: 110 dB
Input Ranges: 0.1, 1.0, 10.0 V Full Scale
Input Impedance: 100 kΩ symmetric for Diff.; 100 kΩ with 50Ω shield to GND for SE
Max Input Voltage: 80vPeak, 2.5vRmsShield (SE)
CMRR: 60 dB (typical), f<40 kHz
Amplitude Accuracy: +/- 0.020dB (0.2%FS) at 1kHz for 15degC < T < 40degC
Amplitude Ripple: (Digital AAF) - 0.005dB for 0 < f < fS / 2.56
Amplitude Droop: (Analog AAF) - 0.005dB at 5kHz; 0.010dB at 25kHz; 0.050dB at 49kHz
Residual Offset: +/- 0.1% FS AND not larger than 3mvDC
Phase Accuracy: 0.05deg to 0.5deg for DC to 40kHz
Crosstalk between Inputs: <-100 dB
Crosstalk between inputs and source:< -90 dB
THD: 100 dB @ 1 kHz
Minimum SampleRate: less than 1Sps
Maximum SampleRate: 204.8 kHz
Maximum useful Frequency: 40 kHz standard, 93 kHz optional
Frequency Accuracy: 25ppm
Time Accuracy: 25ppm



TACHOMETER INPUT



1 per channel
Max. Frequency: 200 kHz
Input Range: +/-24 V FS
Adjustable threshold, holdoff, prescaling

OUTPUT

1 to 2 per channel
Dynamic Range: greater than 100 dB
Resolution: 24 bit
Voltage range: 10 V FS
Output Current: 1 mA min.; continuous short
THD: -100 dB @ 1 kHz
Output Waveforms: 65536 max blocksize for arbitrary; unlimited for recorded (optional)

CHASSIS DETAILS

Dimensions: 5.6" x 4.0" x 0.9"
Weight: 1.2 lbs
Operating Temperature: 0 to 55˚ C
Power: USB 2.0 Bus Powered
Lights: Input OK (4), Output Active (2), Trigger Signal (1), DSP Active (1), USB Active (1)

NOTE: Continued product improvement necessitates that Data Physics reserve the right to modify these specifications without notice.

Model Number 086D05	IMPACT HAMMER, ICP®	Revision G ECN #: 32387

Performance	ENGLISH	SI	
Sensitivity (±15 %)	1 mV/lbf	0.23 mV/N	
Measurement Range	±5000 lbf pk	±22240 N pk	
Resonant Frequency	≥22 kHz	≥22 kHz	
Non-Linearity	≤1 %	≤1 %	
Electrical			
Excitation Voltage	20 to 30 VDC	20 to 30 VDC	
Constant Current Excitation	2 to 20 mA	2 to 20 mA	
Output Impedance	<100 ohm	<100 ohm	[1]
Output Bias Voltage	8 to 14 VDC	8 to 14 VDC	
Discharge Time Constant	≥2000 sec	≥2000 sec	[1]
Physical			
Sensing Element	Quartz	Quartz	
Sealing	Epoxy	Epoxy	
Hammer Mass	0.7 lb	0.32 kg	
Head Diameter	1.0 in	2.5 cm	
Tip Diameter	0.25 in	0.63 cm	
Hammer Length	9.0 in	22.7 cm	
Electrical Connection Position	Bottom of Handle	Bottom of Handle	
Extender Mass Weight	7.0 oz	200 gm	
Electrical Connector	BNC Jack	BNC Jack	

CE[2]

All specifications are at room temperature unless otherwise specified.
In the interest of constant product improvement, we reserve the right to change specifications without notice.
ICP® is a registered trademark of PCB group, Inc.

Optional Versions (Optional versions have identical specifications and accessories as listed for standard model except where noted below. More than one option maybe used.)
T - TEDS Capable of Digital Memory and Communication Compliant with IEEE P1451.4
TLD - TEDS Capable of Digital Memory and Communication Compliant with IEEE 1451.4

Notes
[1] Typical.
[2] See PCB Declaration of Conformance PS068 for details.

Supplied Accessories
081B05 Mounting Stud (10-32 to 10-32) (2)
084A09 Extender - steel, 1.0" diameter (1)
084A50 Tip - super soft- Grey 15.101 1" 10SS (1)
084A51 Adaptor for 084A50 (1)
084B03 Hard Tip- Hard (S.S) (1)
084B04 Hammer Tip- Medium (White Plastic) (1)
084C05 Hammer Tip- Soft (Black) (2)
085A10 Vinyl Cover For Medium Tip (Blue) (2)
HCS-2 Calibration of Series 086 instrumented impact hammers (1)

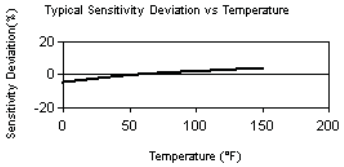
Entered: LLH	Engineer: DJS	Sales: JJM	Approved: EB	Spec Number:
Date: 02/24/2010	Date: 12/08/2009	Date: 02/17/2010	Date: 02/17/2010	**20713**

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Web site: www.pcb.com

Model Number 333B32	ACCELEROMETER, ICP®	Revision G ECN #: 31217

	ENGLISH	SI	
Performance			
Sensitivity (±10 %)	100 mV/g	10.2 mV/(m/s²)	
Measurement Range	±50 g pk	±490 m/s² pk	
Frequency Range (±5 %)	0.5 to 3000 Hz	0.5 to 3000 Hz	
Resonant Frequency	≥40 kHz	≥40 kHz	
Phase Response (±5 °) (at 70&#176F [21&#176C])	2 to 3000 Hz	2 to 3000 Hz	
Broadband Resolution (1 to 10000 Hz)	0.00015 g rms	0.0015 m/s² rms	[1]
Non-Linearity	≤1 %	≤1 %	[2]
Transverse Sensitivity	≤5 %	≤5 %	
Environmental			
Overload Limit (Shock)	±5000 g pk	±49000 m/s² pk	
Temperature Range (Operating)	0 to +150 °F	-18 to +66 °C	
Temperature Response	See Graph	See Graph	[1]
Base Strain Sensitivity	0.01 g/με	0.1 (m/s²)/με	[1]
Electrical			
Excitation Voltage	18 to 30 VDC	18 to 30 VDC	
Constant Current Excitation	2 to 20 mA	2 to 20 mA	
Output Impedance	≤300 ohm	≤300 ohm	
Output Bias Voltage	7 to 12 VDC	7 to 12 VDC	
Discharge Time Constant	1.0 to 3.0 sec	1.0 to 3.0 sec	
Spectral Noise (10 Hz)	11 μg/√Hz	110 (μm/sec²)/√Hz	[1]
Spectral Noise (100 Hz)	3.4 μg/√Hz	33 (μm/sec²)/√Hz	[1]
Spectral Noise (1 kHz)	1.4 μg/√Hz	14 (μm/sec²)/√Hz	[1]
Physical			
Sensing Element	Ceramic	Ceramic	
Sensing Geometry	Shear	Shear	
Housing Material	Titanium	Titanium	
Sealing	Hermetic	Hermetic	
Size (Length x Width)	0.63 in x 0.40 in	16.0 mm x 10.2 mm	
Weight	0.14 oz	4.0 gm	[1]
Electrical Connector	10-32 Coaxial Jack	10-32 Coaxial Jack	
Electrical Connection Position	Side	Side	
Mounting	Adhesive	Adhesive	

CE[3]



All specifications are at room temperature unless otherwise specified.
In the interest of constant product improvement, we reserve the right to change specifications without notice.
ICP® is a registered trademark of PCB group, Inc.

Optional Versions (Optional versions have identical specifications and accessories as listed for standard model except where noted below. More than one option maybe used.)

T - TEDS Capable of Digital Memory and Communication Compliant with IEEE P1451.4
TLA - TEDS LMS International - Free Format
TLB - TEDS LMS International - Automotive Format
TLC - TEDS LMS International - Aeronautical Format
TLD - TEDS Capable of Digital Memory and Communication Compliant with IEEE 1451.4

Excitation Voltage	19 to 30 VDC	19 to 30 VDC
Output Bias Voltage	7.5 to 13 VDC	7.5 to 13 VDC

Notes
[1] Typical.
[2] Zero-based, least-squares, straight line method.
[3] See PCB Declaration of Conformance PS023 for details.

Supplied Accessories
080A109 Petro Wax (1)
080A90 Quick Bonding Gel (1)
ACS-1 NIST traceable frequency response (10 Hz to upper 5% point). (1)

Entered: LLH	Engineer: MJN	Sales: WDC	Approved: EB	Spec Number:
Date: 08/18/2009	Date: 08/13/2009	Date: 08/13/2009	Date: 08/14/2009	**11829**

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GE
Inspection Technologies

Phasor XS™

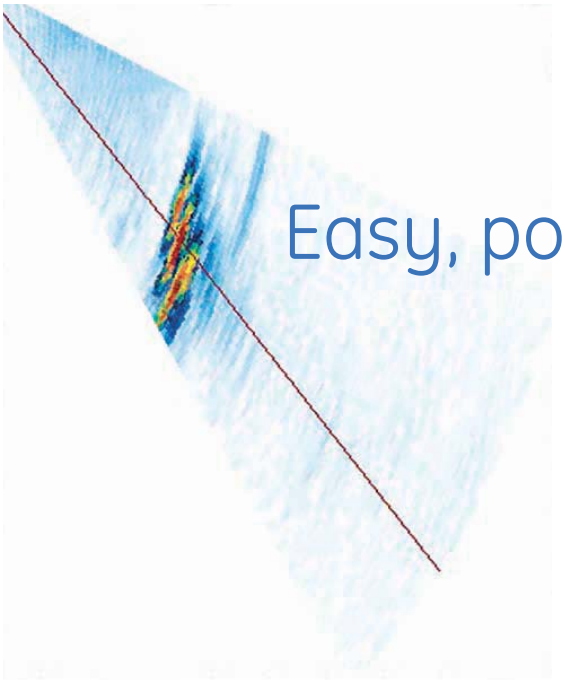
Portable Phased Array Ultrasonic Flaw Detector



Combining the power of Phased Array with the comfort of conventional flaw detection at an accessible price.

The GE Phasor XS is your companion for improving everyday inspections.

GE imagination at work



Easy, portable and affordable

When used in Phased Array mode, the operator simply programs the transducer for multiple angles and focal depths without changing probes or wedges. Sector Scan with precise beam control results in improved probability of detection (POD) and sizing. With one scan from one contact location, greater area is covered and comprehensive data can be viewed in real-time on a full-color sector display. Compared to conventional ultrasonic inspection, the productivity and cost savings of the Phasor XS make it an easy decision for the NDT professional.



Transitioning from conventional to Phased Array-based flaw detection is now easy. The Phasor XS weighs less than 4 kgs and has the same look, feel and rugged design as the popular USN 60. In fact, the Phasor XS can be operated as a conventional flaw detector. Simple menu-driven operation of basic Phased Array controls puts the technology within reach of the Level II field inspector. Data is easily captured and interpreted. The cost of training is minimized.

Sector Scan Capability

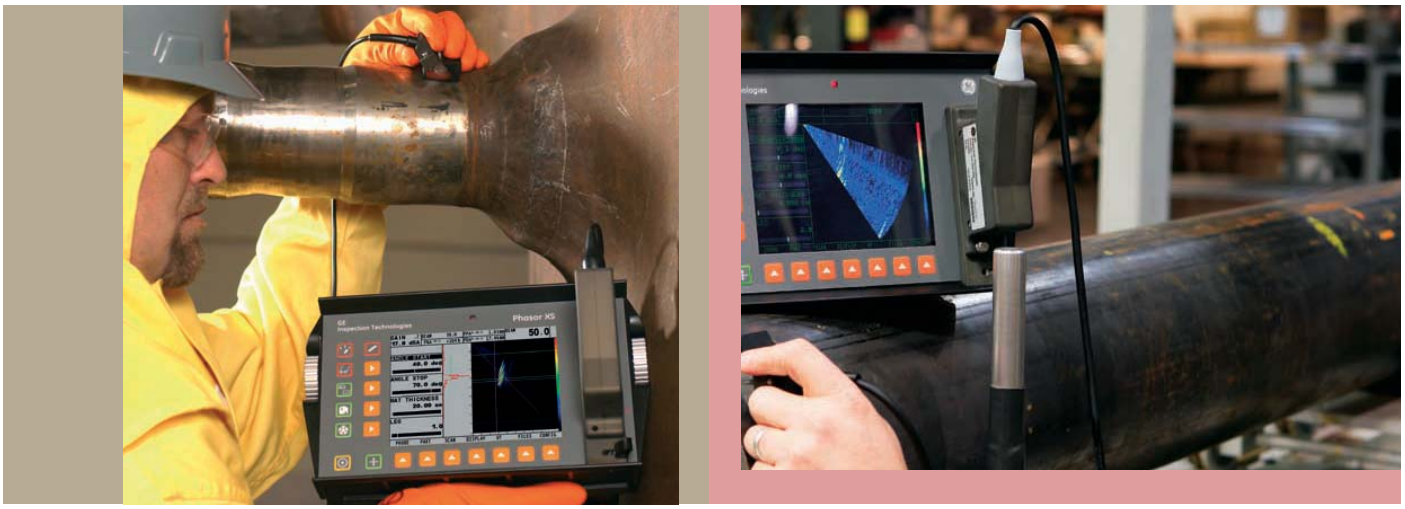
Sector Scan capability in the Phased Array mode significantly improves probability of detection while gaining productivity by scanning a larger volume in a single scan. Phasor XS supports up to 64 element physical probes and is capable firing up to 16 elements for beam forming. The easy to use on-board delay law calculator makes it simple and fast to program the tranducer.

Advanced Measurement Tools

Phasor XS supports a full complement of measurement tools. Two sets of cursors allow for signal sizing and true depth measurement while horizontal location measurement is also possible. User-friendly color schemes make measurement simple and quick.

User-friendly Interface

The Phasor XS features a 6.5" VGA display with a best-in-class 60 Hz data refresh rate and a choice of selectable screen options that allow optimum viewing even in the most difficult field conditions. Several options are available including unique views such as Video Reverse which allows users to align the sector view with the probe. Selectable A-Scans can also be viewed along with the Sector Scan.



Rapid Reporting

JPEG images, sector scans or other views can be stored with a single key press as part of the unique Freeze Mode and down-loaded in image-ready format to an SD™ solid-state memory card for fast documentation or report generation.

Multiple Phased Array Transducer Options

GE Inspection Technologies manufactures a wide variety of Phased Array transducers that are applicable to Phasor XS.



Phased Array transducers with Dialog feature recognize physical connection and automatically download transducer information to Phasor XS.
A catalog of both conventional and Phased Array transducers is available at: www.ge.com/phasorxs

Feature Summary

- Ultra-portable Phased Array at less than 3.8 kg (8.2 lbs)
- Industry standard code-compliant flaw detector
- Electronically controlled and selectable beam angles, focus and size
- Simultaneous inspection with multiple beams from a single location
- Simple operation allows for easy transition from conventional UT to Phased Array inspection
- Field-proven rugged packaging to withstand heavy on-site use
- Full-color, real-time sector display with selectable A-Scan
- Full-screen display and snap-shot image storage of sector images, A-Scans, B-Scans, measurement and on-screen set-up parameters
- JPEG image reporting and data-set transfer via SD memory card
- On-board delay law calculator
- Push-button control for ease-of-use and operation within a sealed bag for anti-contamination

Product code	Frequency	Elements							Cable Length	
		Count	Aperture		Elevation		Pitch			
	MHz		mm²	inch²	mm	inch	mm	inch	m	ft
L8U84	2	8	8 x 9	.31 x .35	9	.35	1	.039	2	6.5
L8U96	4	16	8 x 9	.31 x .35	9	.35	0.5	.020	2	6.5
EUN75	5	32	16 x 10	.63 x .39	10	.39	0.5	.020	2	6.5
L99HK	5	16	16 x 10	.63 x .39	10	.39	1	.039	2	6.5
L99KO	2.25	16	16 x 13	.63 x .51	13	.51	1	.039	2	6.5
L99LQ	2.25	16	24 x 19	.94 x .75	19	.75	1.5	.059	2	6.5
L99JM	5	64	64 x 10	2.5 x .39	10	.39	1	.039	2	6.5

List of standard transducers as of product launch.

Technical Specifications

Physical Specifications

Internal Memory	Set-up files
Removable Memory	On 512 MB SD Card for report and set-up files
Documentation Format	JPEG ~80 KB/image
Weight	3.8 kg (8.2 lbs) with battery
Dimensions	282 mm W x 171 mm H x 159 mm D (11.1 in. W x 6.8 in. H x 6.3 in. D)
Battery	Custom Li Ion battery pack - 356P configuration
Battery Life	6 hrs minimum
Battery Charging	External charger
External Power Supply	Universal input 85 to 260 V AC / 50 to 60 Hz
Probe Connectors	Conventional - 00 lemo/BNC adapters provided - Phased Array - Custom ZIF
VGA Output	Yes
Dialog Languages	Chinese, English, French, German, Italian, Japanese, and Spanish
Display Size	165 mm (6.5 in.) diagonal
Display Resolution	VGA color TFT 640H x 480V pixel

Conventional / Phased Array Channel Specifications

	Conventional	Phased Array
Pulser	Spike	Bi-Polar Square Wave
Pulse Repetition Frequency	15 to 2000 Hz	15 to 7680 Hz
Pulser Voltage	300 V max	± 25 V to ± 75 V (1 V steps)
Pulser Energy	Low or High (selectable)	
Pulser Rise Time	< 15 nsec	< 15 nsec
Damping	50 or 1000 Ohms (selectable)	
Mode of operation	single, dual	single
Receiver Input Capacitance	< 50 pF	
Receiver Input Resistence	1000 Ohms in dual mode	220 Ohms
Maximum Input Voltage	40 V peak-to-peak	200 mV peak-to-peak
Bandwidth/Amplifier BandPath	0.3 to 15 MHz @ -3dB	selectable
Frequency Selection	1.0, 2.0, 2.25, 4.0, 5.0, 10 and 15 MHZ + BB	2.25, 4.0, and 5.0 MHZ + LP & HP
Rectification	Pos HW, Neg HW, FW, and RF	Pos HW, Neg HW, FW and RF
Analog Gain	0 to 110 dB	0 to 40 dB
Digital Gain		0 to 53.9 dB
Focal Laws		User selectable - 128 max
Physical Probe		1 to 64
Virtual Probe		1 to 16
Number of Cycles		1 to 128
Pulser Width @ 1/2 Cycle		20 to 500 nsec
Pulser Delay		0 to 10.24 µ-sec
Receiver Delay		0 to 10.24 µ-sec
Acoustic Velocity	1000 to 16000 m/s 0.0393 to 0.5905 in./µ-sec	1000 to 16000 m/s 0.0393 to 0.5905 in./µ-sec
Minimum Range (steel long)	0 -14 mm (0.55 inch)	0 - 7.6 mm (0.3 inch)
(steel shear)	0 - 7.5 mm (0.3 inch)	0 - 4.2 mm (0.17 inch)
Maximum Range (steel long)	0 - 14060 mm (553 inch)	0 - 1073 mm (42 inch)
(steel shear)	0 - 7626 mm (300 inch)	0 - 1073 mm (42 inch)
Display Delay	2.5 m (98.5 inch)	1 m (39.4 inch)
Auto Timebase Calibration	Yes	
Reject	0 to 80%	0 to 80%
TCG	15 points @ 6 dB/µ-sec	15 points @ 6 dB/µ-sec
Gates	A and B	A, B and IF
Gate Threshold	5 to 95%	5 to 95%
Gate Start	0 mm - full range	0 mm - full range
Gate Width	1 mm - full range	1 mm - full range
Gate Logic	Off, Positive, and Negative (Off, Coincidence, and Anticoincidence)	Off, Positive, and Negative (Off, Coincidence, and Anticoincidence)
TOF Modes	Flank/Peak	Flank/Peak
Scan Type		Linear and Sector
Available Views	A-Scan	A-Scan, B-Scan and Sector
Displayed Readings	Amplitude, Sound Path, and Trig	Beam, Amplitude, Sound Path, Trig for displayed and for all beams
Measurement Resolution	5 nsec	5 nsec
Displayed Units of Measurements	mm or inch (selectable)	mm or inch (selectable)

All blank fields are non-applicable

Environmental Tests

Per Mil-Std-810F	
Cold Storage	-20°C for 72 hrs, 502.4 Procedure I
Cold Operation	0°C for 16 hrs, 502.4 Procedure II
Heat Storage	+70°C for 48 hrs, 501.4 Procedure I
Heat Operation	+50°C for 16 hrs, 501.4 Procedure II
Damp Heat / Humidity (storage)	10 Cycles: 10 hrs at +65°C down to +30°C, 10 hrs at +30°C up to +65°C, transitions within 2 hrs, 507.4
Temperature Shock	3 Cycles: 4 hrs at –20°C up to +70°C, 4 hrs at +70°C, transitions within 5 mins. 503.4 Procedure II
Vibration	514.5-5 Procedure I, Annex C, Figure 6, general exposure: 1 hr each axis
Shock	6 cycles each axis, 15g, 11ms half sine, 516.5 Procedure I
Loose Cargo	514.5 Procedure II
Transit Drop (packaged for shipment)	516.5 Procedure IV, 26 drops
IP54 / IEC529 ... dust proof / dripping water proof as per IEC 529 specifications for IP54 classification	

Specifications subject to change without notice.

www.ge.com/phasorxs

GE Inspection Technologies: productivity through inspection solutions

GE Inspection Technologies provides technology-driven inspection solutions that deliver productivity, quality and safety. We design, manufacture and service Ultrasonic, Remote Visual, Radiographic and Eddy Current equipment and systems. Offering specialized solutions that will help you improve productivity in your applications in the Aerospace, Power Generation, Oil & Gas, Automotive or Metals Industry. Contact your GE Inspection Technologies representative or visit **www.ge.com/inspectiontechnologies** for more information.

Phasor XS is a trademark of GE Inspection Technologies. SD is a trademark of the SD Card Association.
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Large Panel Four-point Flexural Static Testing

Instron ±1500 kN (±337 Kip) servo-hydraulic actuator	AEWC # 262
Instron ±1500 kN (±337 Kip) load cell	AEWC # 939
Computer (PC running WaveMatrix and D.A. software)	AEWC # 956
NI SCXI-1001 data aquisition system chassis	AEWC # 342
NI SCXI voltage input module (load & position data)	AEWC # 885
NI SCXI strain gage module	AEWC # 875
NI SCXI voltage input module (string-pot data)	AEWC # 874
Computer (PC running Labview software)	AEWC # 350
String potentiometers	25 in.-#26 25 in.-#29 25 in.-#35

Large Panel Four-point Flexural Fatigue Testing

Instron ±250 kN (±56.2 Kip) servo-hydraulic actuator	AEWC # 264
Instron ±250 kN (±56.2 Kip) load cell	AEWC # 650
Computer (PC running WaveMatrix and D.A. software)	AEWC # 694

ASTM C273 Sandwich Core Shear Testing

Instron 8801 servo-hydraulic test machine	AEWC # 107
Instron ±100 kN (±22.5 kip) load cell	AEWC # 268
Computer (PC running Instron control and D.A. software)	AEWC # 795
NI SCXI-1001 Labview data acquisition system chassis	AEWC # 538
NI SCXI voltage input module (load & position data)	AEWC # 862
NI SCXI LVDT input module	AEWC # 852
Computer (PC running Labview software)	AEWC # 790
Russells environmental chamber	AEWC # 126
ASTM C273 test fixture	AEWC # 303
LVDTs	1 in. LVDT#10 1 in. LVDT#15 1 in. LVDT#17 (replaced #10)

ASTM C393 Sandwich Beam Flexural Testing

Parker Hannifin hydraulic acutator	AEWC # 643
Instron ±100 kN (±22.5 kip) load cell	AEWC # 645
Computer (PC running Instron control and D.A. software)	AEWC # 693
NI SCXI-1001 data acquisition system chassis	AEWC # 543
NI SCXI voltage input module (string pots, load & position)	AEWC # 854
Computer (PC running Labview software)	AEWC # 546
Russells environmental chamber	AEWC # 126
String potentiometers	25 in.-#26 25 in.-#29 25 in.-#35

ASTM D3039 Tension Specimen Preparation and Testing

Mitutoyo 0-8.0" Digital Caliper	AEWC # 685
Mitutoyo 0-1.0" Digital Micrometer	AEWC # 659
Instron 8801 servo-hydraulic test machine	AEWC # 107
Instron ±100 kN (±22.5 Kip) load cell	AEWC # 268
Computer (PC running Instron control and D.A. software)	AEWC # 795
NI SCXI-1001 data aquisition system chassis	AEWC # 538
NI SCXI voltage input module (load & position data)	AEWC # 862
NI SCXI strain gage module	AEWC # 872
Computer (PC running Labview software)	AEWC # 790
Aramis 3-D Digital Image Correlation Workstation	

ASTM D6641 Compression Specimen Preparation and Testing

Mitutoyo 0-8.0" Digital Caliper	AEWC # 685
Mitutoyo 0-1.0" Digital Micrometer	AEWC # 659
Instron 8801 servo-hydraulic test machine	AEWC # 107
Instron ±100 kN (±22.5 Kip) load cell	AEWC # 268
Computer (PC running Instron control and D.A. software)	AEWC # 795
NI SCXI-1001 data acquisition system chassis	AEWC # 538
NI SCXI voltage input module (load & position data)	AEWC # 862
NI SCXI strain gage module	AEWC # 872
Computer (PC running Labview software)	AEWC # 790
Combined Loading Compression Fixture	AEWC # 293
Aramis 3-D Digital Image Correlation Workstation	

ASTM D5379 V-Notch Shear Specimen Preparation and Testing

Mitutoyo 0-8.0” Digital Caliper	AEWC # 685
Mitutoyo 0-1.0” Digital Micrometer	AEWC # 659
Instron 8874 servo-hydraulic test machine	AEWC # 512
Lebow 3173 ±4.5 kN (±1.0 Kip) load cell	AEWC # 656
Computer (PC running Instron control and D.A. software)	AEWC # 797
Wyoming Iosipescu Shear Test Fixture	AEWC # 301
Aramis 3-D Digital Image Correlation Workstation	

ASTM D3171 Constituent Content Specimen Testing

OHaus Voyager Pro (0.01 mg) Scale	AEWC # 657
Fisher Scientific Muffle Furnace	AEWC # 180

Through-Thickness Compression Specimen Preparation and Testing

Mitutoyo 0-8.0” Digital Caliper	AEWC # 685
Mitutoyo 0-1.0” Digital Micrometer	AEWC # 659
Instron 8803 servo-hydraulic test machine	AEWC # 270
Instron ±500 kN (±112 Kip) load cell	AEWC # 408
Computer (PC running Instron control and D.A. software)	AEWC # 793
NI SCXI-1001 data acquisition system chassis	AEWC # 538
NI SCXI voltage input module (load & position data)	AEWC # 862
NI SCXI strain gage module	AEWC # 872
Computer (PC running Labview software)	AEWC # 790
Aramis 3-D Digital Image Correlation Workstation	

ASTM D5528 Mode-I Interlaminar Fracture Specimen Preparation and Testing

Mitutoyo 0-8.0” Digital Caliper	AEWC # 685
Mitutoyo 0-1.0” Digital Micrometer	AEWC # 659
Instron 8874 servo-hydraulic test machine	AEWC # 512
Instron ±250 N (±56.2 lb.) load cell	AEWC # 611
Computer (PC running Instron control and D.A. software)	AEWC # 797

Mode-II Interlaminar Fracture Specimen Preparation and Testing

Mitutoyo 0-8.0” Digital Caliper	AEWC # 685
Mitutoyo 0-1.0” Digital Micrometer	AEWC # 659
Instron 8874 servo-hydraulic test machine	AEWC # 512
Lebow 3173 ±4.5 kN (±1.0 Kip) load cell	AEWC # 656
Computer (PC running Instron control and D.A. software)	AEWC # 797
Three-point Flexure Fixture	AEWC # 298

Appendix D
HDC Panel Infusion Data Sheets

Pages 306-462 Available in PDF format ONLY

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 1-B

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-B***

Data Sheet for Infusing Composite Structures

Date: 10/18/2010 **Shop Temperature:** 74 °F

Name(s): Donald Soohey **Humidity:** 26.4 %RH
John Levins

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		CFM			√
2		E LT 1603			√
3		E LT 2415			√
4		E LT 3610			√
5		E LT 3610			√
6		H130 (1.5)			√
7		CFM			√
8		H130 (1.5)			√
9		E LT 3610			√
10		E LT 3610			√
11		E LT 2415			√
12		E LT 1603			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-B***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 10/19/2010 **Shop Temperature:** 74 °F

Name(s): Donald Soohey **Humidity:** 25.9 %RH

Start: 12:00 AM / **PM** Vacuum Level: 27 ½ "of Hg
Stop: 12:15 AM / **PM** Vacuum Level: 27 ½ "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-B***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 10/19/2010 **Shop Temperature:** 74 °F

Name(s): Donald Soohey **Humidity:** 25.9 %RH
John Levins

Infusion:

Start: 1:30 AM / **PM** Temp: 74 °F Vacuum Level: 27 ½ "of Hg
Stop: 1:50 AM / **PM** Temp: °F Vacuum Level: 27 ½ "of Hg

Comments: Infused in 20 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 1-B-C-2

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-B-C-2***

Data Sheet for Infusing Composite Structures

Date: 10/28/2010 **Shop Temperature:** 72.5 °F

Name(s): Donald Soohey **Humidity:** %RH
John Levins

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		CFM			√
2		E LT 1603			√
3		E LT 2415			√
4		E LT 3610			√
5		E LT 3610			√
6		H130 (1.5)			√
7		CFM			√
8		H130 (1.5)			√
9		E LT 3610			√
10		E LT 3610			√
11		E LT 2415			√
12		E LT 1603			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-B-C-2***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 10/28/2010 **Shop Temperature:** 72.9 °F

Name(s): John Levins **Humidity:** %RH

Start: 1:25 AM / **PM** Vacuum Level: 26 "of Hg
Stop: 1:40 AM / **PM** Vacuum Level: 25 ½ "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-B-C-2***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 10/28/2010 **Shop Temperature:** 72.9 °F

Name(s): Donald Soohey **Humidity:** %RH
John Levins

Infusion:

Start: 2:25 AM / **PM** Temp: 76 °F Vacuum Level: 26 ¼ "of Hg
Stop: 2:40 AM / **PM** Temp: 82 °F Vacuum Level: 26 ¼ "of Hg

Comments: Fully Wet Out in 15 minutes.

Kept Feed Line open for 40 Minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 1-B-S

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-B-S***

Data Sheet for Infusing Composite Structures

Date: 10/20/2010 **Shop Temperature:** 74 °F

Name(s): John Levins **Humidity:** 28.9 %RH
Donald Soohey

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		CFM			√
2		E LT 1603			√
3		E LT 2415			√
4		E LT 3610			√
5		E LT 3610			√
6		H130 (1.5)			√
7		CFM			√
8		H130 (1.5)			√
9		E LT 3610			√
10		E LT 3610			√
11		E LT 2415			√
12		E LT 1603			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-B-S***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 10/25/2010 **Shop Temperature:** 71 °F

Name(s): John Levins **Humidity:** 27.6 %RH

Start: 9:20 **AM** / PM Vacuum Level: 30 ¼ "of Hg
Stop: 9:40 **AM** / PM Vacuum Level: 30 ¾ "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-B-S***

Data Sheet for
Infusing Composite Structures

INFUSION DATA

Date: 10/25/2010 **Shop Temperature:** 71 °F

Name(s): John Levins **Humidity:** 27.6 %RH
Donald Soohey

Infusion:

Start: 10:50 **AM** / PM Temp: 71 °F Vacuum Level: 30 ½ "of Hg
Stop: 11:40 **AM** / PM Temp: 77 °F Vacuum Level: 30 ½ "of Hg

Comments: Infused in 50 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 1-M-C Redo

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-M-C***

Data Sheet for Infusing Composite Structures

Date: 1/04/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

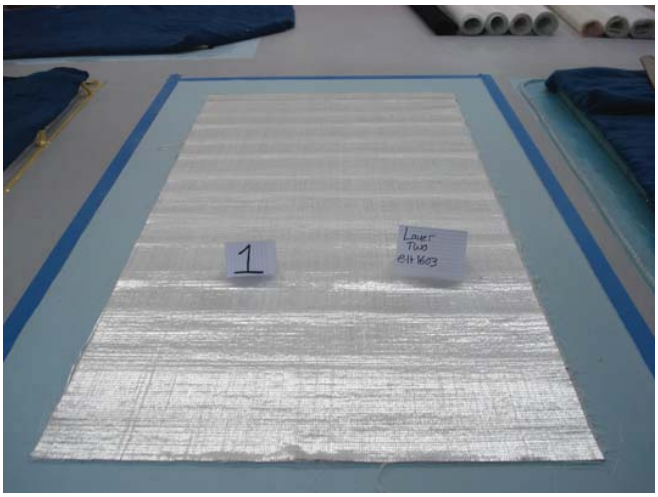
Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		CFM			√
2		E LT 1603			√
3		E LT 2415			√
4		E LT 3610			√
5		E LT 3610			√
6		H130 (1.5)			√
7		CFM			√
8		H130 (1.5)			√
9		E LT 3610			√
10		E LT 3610			√
11		E LT 2415			√
12		E LT 1603			√

Core Thickness: __

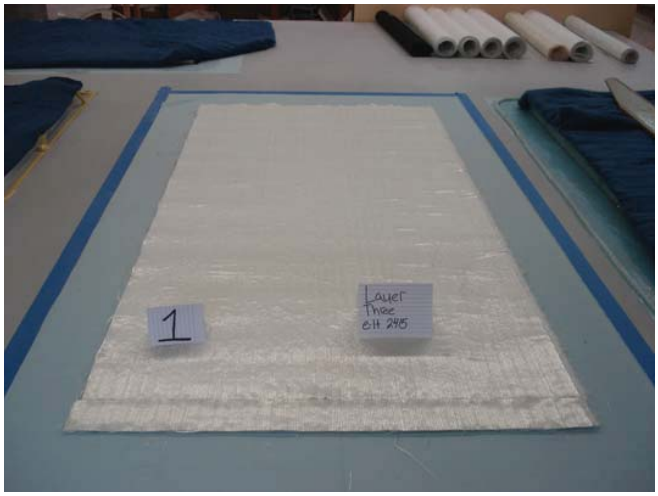
HODGDON SHIPBUILDING



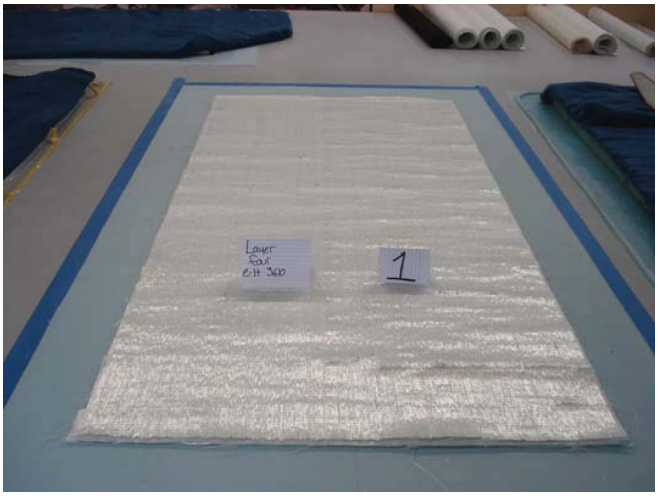
1st Layer – CFM



2nd Layer – E-LT 1603

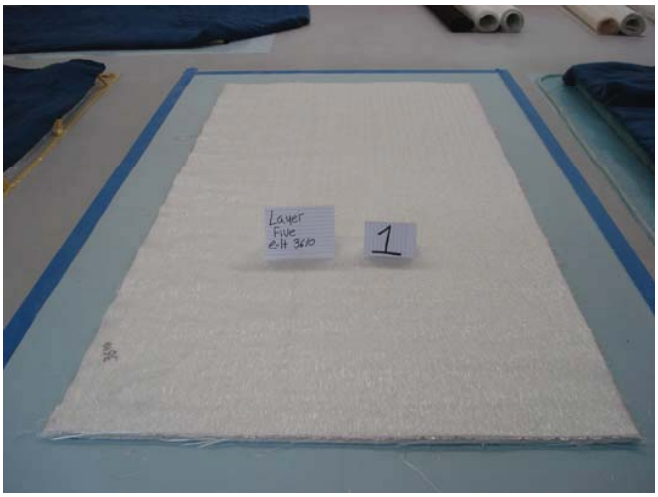


3rd Layer – E-LT 2415

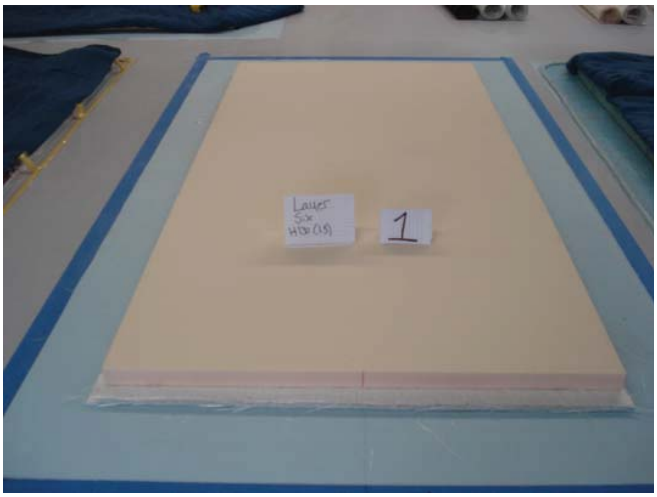


4th Layer – E-LT 3610

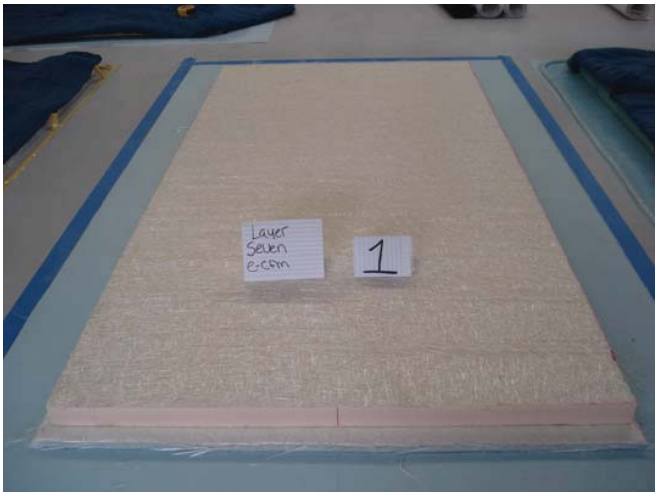
HODGDON SHIPBUILDING



5th Layer – E-LT 3610



6th Layer – H130 (1.5) Core

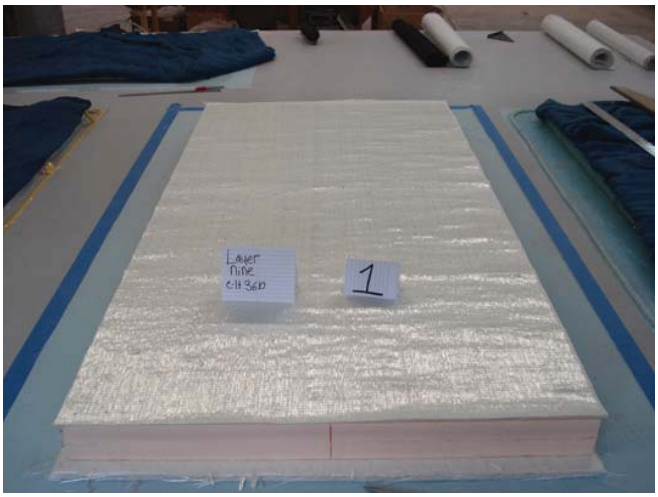


7th Layer – CFM

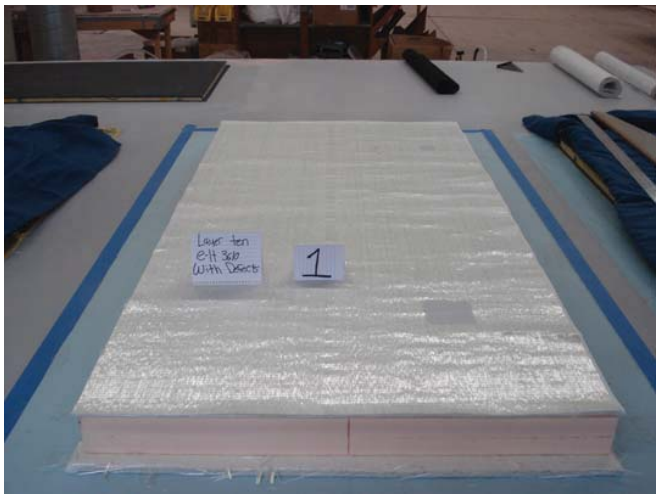


8th Layer – H130 (1.5) Core

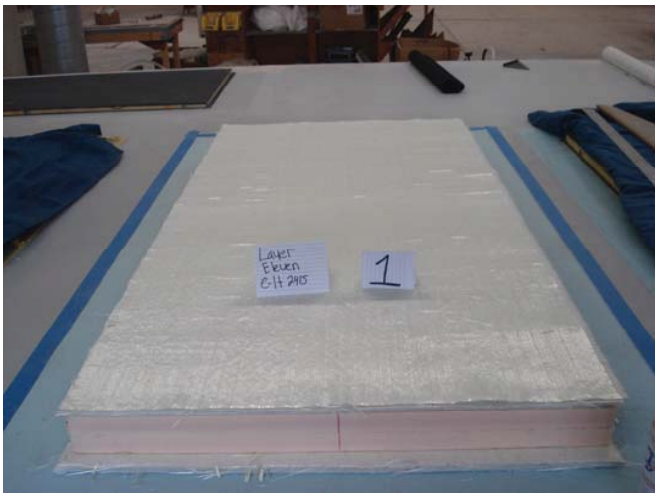
HODGDON SHIPBUILDING



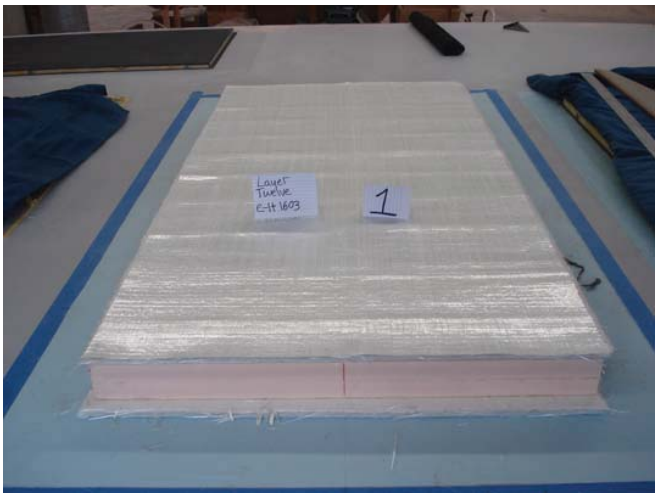
9th Layer – E-LT 3610



10th Layer – E-LT 3610



11th Layer – E-LT 2415



12th Layer – E-LT 1603

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-M-C***

Data Sheet for Infusing Composite Structures

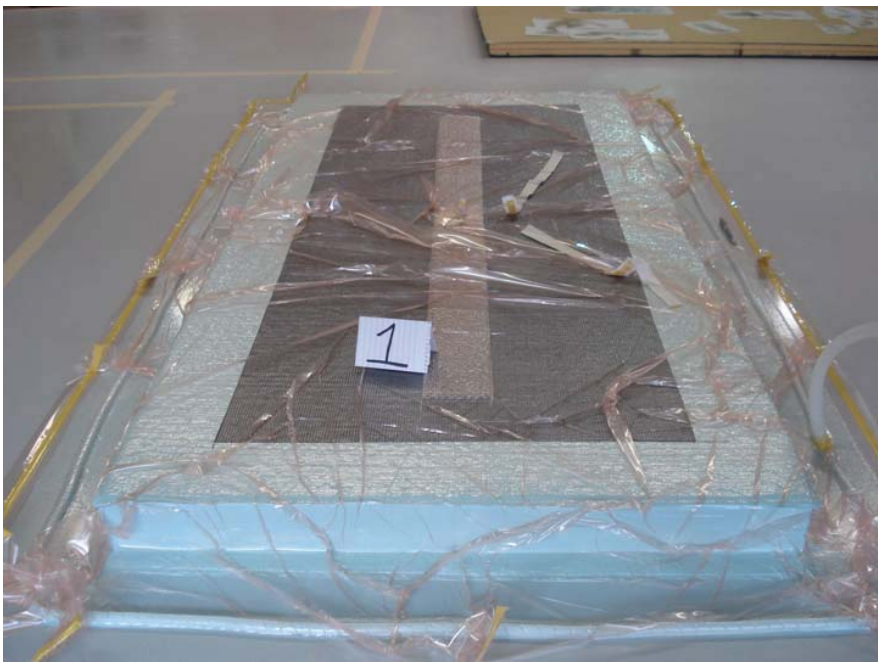
VACUUM INTEGRITY TEST POST LAY-UP

Date: 1/04/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

Start: 12:20 AM / **PM** Vacuum Level: 30 "of Hg
Stop: 12:35 AM / **PM** Vacuum Level: 30 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-M-C***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 1/04/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

Infusion:

Start:	1:12 AM / **PM**	Temp:	71.5 °F	Vacuum Level:	30 "of Hg
Stop:	1:51 AM / **PM**	Temp:	73.5 °F	Vacuum Level:	30 "of Hg

Comments: Infused in 39 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 1-M-S Redo

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-M-S***

Data Sheet for Infusing Composite Structures

Date: 1/04/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

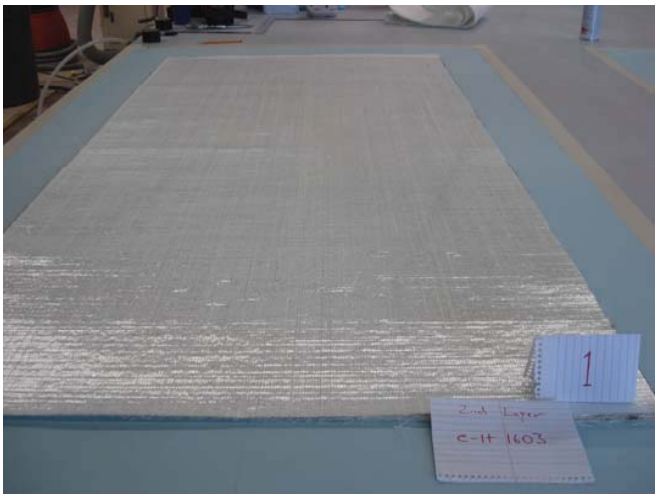
Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		CFM			√
2		E LT 1603			√
3		E LT 2415			√
4		E LT 3610			√
5		E LT 3610			√
6		H130 (1.5)			√
7		CFM			√
8		H130 (1.5)			√
9		E LT 3610			√
10		E LT 3610			√
11		E LT 2415			√
12		E LT 1603			√

Core Thickness: __

HODGDON SHIPBUILDING



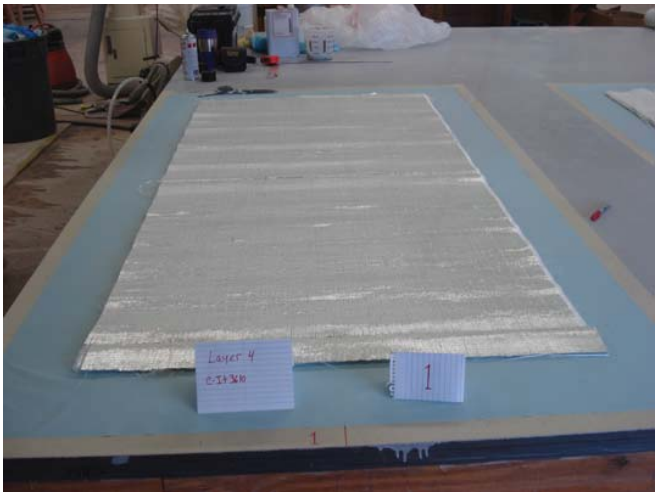
1st Layer – CFM



2nd Layer – E-LT 1603

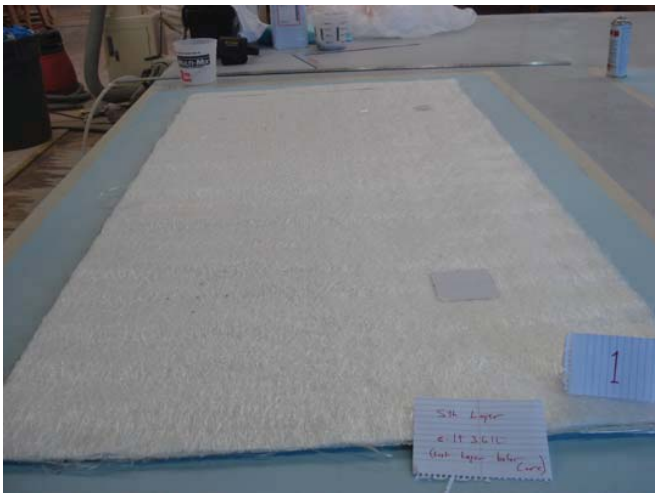


3rd Layer – E-LT 2415 with Defects

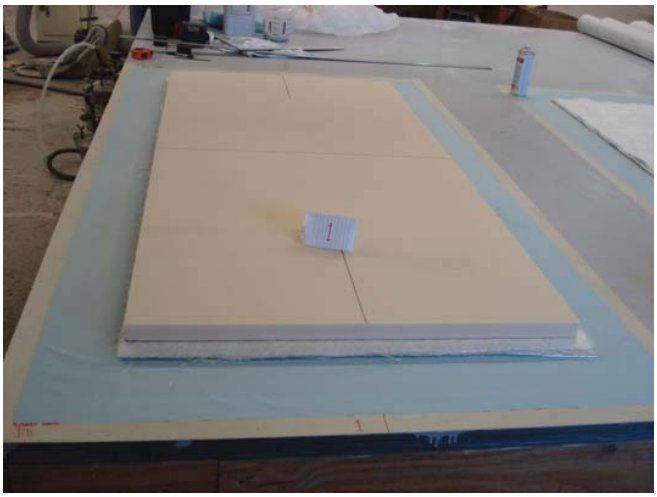


4th Layer – E-LT 3610

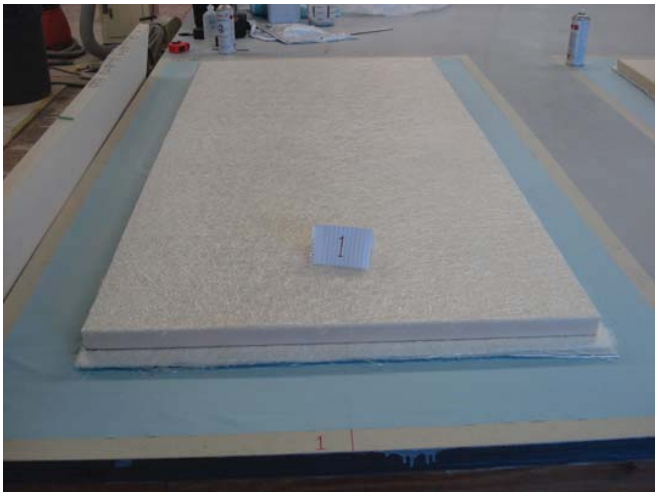
HODGDON SHIPBUILDING



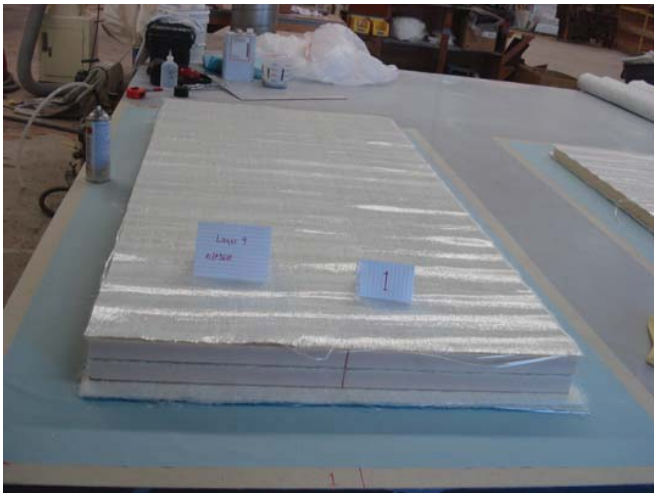
5th Layer – E-LT 3610 with Defects



6th Layer – H130 (1.5) Core



7th Layer – CFM



8th & 9th Layer – H130 (1.5) & E-LT 3610

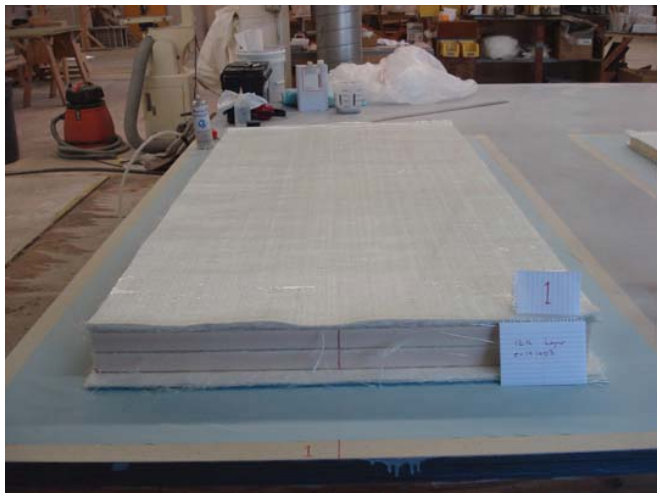
HODGDON SHIPBUILDING



10th Layer – E-LT 3610



11th Layer – E-LT 2415



12th Layer – E-LT 1603

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-M-S***

Data Sheet for Infusing Composite Structures

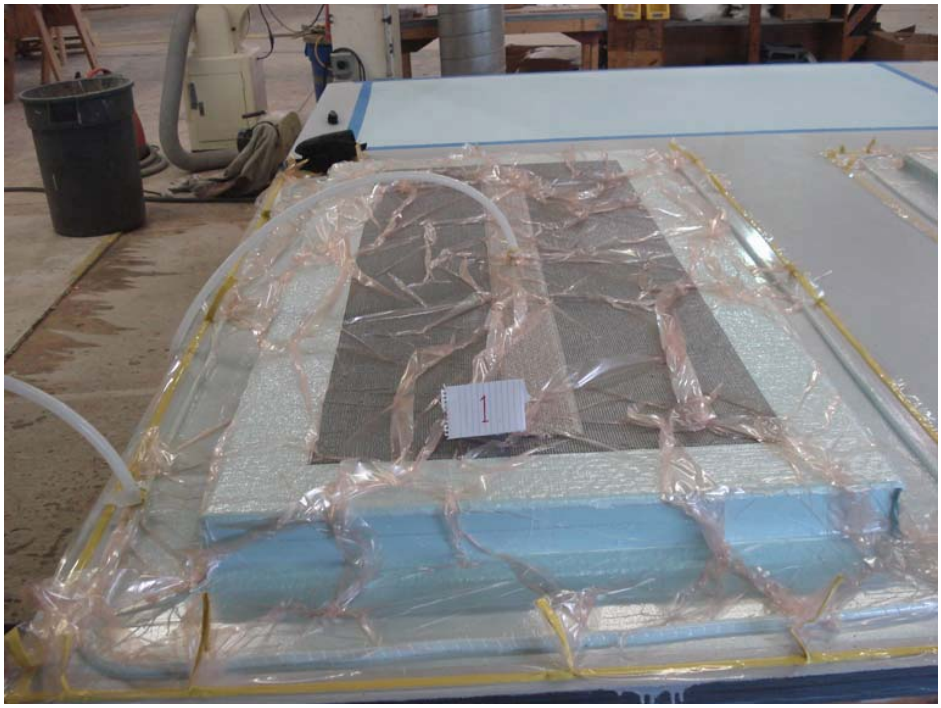
VACUUM INTEGRITY TEST POST LAY-UP

Date: 1/04/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

Start: 12:20 AM / **PM** Vacuum Level: 30 "of Hg
Stop: 12:35 AM / **PM** Vacuum Level: 30 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-M-S***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 1/04/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

Infusion:

Start: 1:12 AM / **PM** Temp: 71.5 °F Vacuum Level: 30 "of Hg
Stop: 1:51 AM / **PM** Temp: 73.5 °F Vacuum Level: 30 "of Hg

Comments: Infused in 39 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 2-B

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-B***

Data Sheet for Infusing Composite Structures

Date: 11/15/2010 **Shop Temperature:** °F

Name(s): Donald Soohey **Humidity:** %RH

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		CFM			√
2		E-LT 1603			√
3		E-LT 3610			√
4		E-LT 3610			√
5		H-100 (1.5)			√
6		E-LT 3610			√
7		E-LT 3610			√
8		E-LT 1603			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-B***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 11/16/2010 **Shop Temperature:** 72 °F

Name(s): Chad Jones **Humidity:** %RH

Start: 10:10 **AM** / PM Vacuum Level: 26.5 "of Hg
Stop: 10:25 **AM** / PM Vacuum Level: 26.25 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-B***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 11/16/2010 **Shop Temperature:** 72.5 °F

Name(s): Donald Soohey **Humidity:** %RH

Infusion:

Start: 11:00 **AM** / PM Temp: 72.6 °F Vacuum Level: 26.5 "of Hg

Stop: 11:16 **AM** / PM Temp: 81 °F Vacuum Level: 26.5 "of Hg

Comments: Infused in 16 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 2-B-C

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-B-C***

Data Sheet for Infusing Composite Structures

Date: 11/17/2010 **Shop Temperature:** °F

Name(s): Donald Soohey **Humidity:** %RH

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		CFM			√
2		E LT 1603			√
3		E LT 3610			√
4		E LT 3610			√
5		H100 (1.5)			√
6		E LT 3610			√
7		E LT 3610			√
8		E LT 1603			√

Core Thickness: 1.5”

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-B-C***

Data Sheet for Infusing Composite Structures

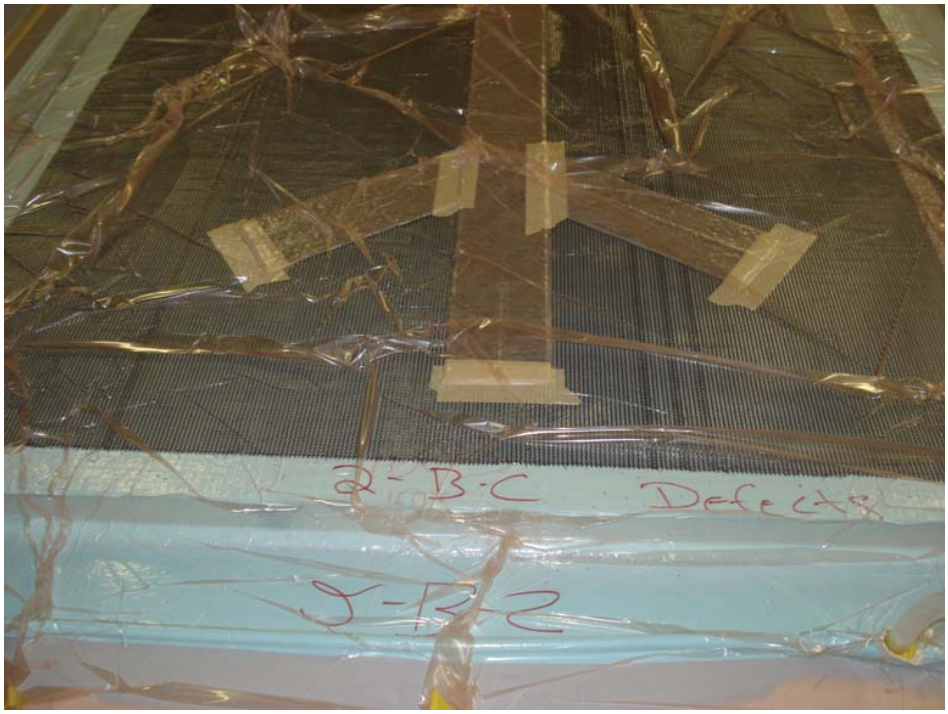
VACUUM INTEGRITY TEST POST LAY-UP

Date: 11/22/2010 **Shop Temperature:** 68 °F

Name(s): Donald Soohey **Humidity:** %RH

Start: 7:55 **AM** / PM Vacuum Level: 26 "of Hg
Stop: 8:10 **AM** / PM Vacuum Level: 25 ½ "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-B-C***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 11/22/2010 **Shop Temperature:** 68 °F

Name(s): Donald Soohey **Humidity:** %RH

Infusion:

Start: 9:45 **AM** / PM Temp: 68 °F Vacuum Level: 26 "of Hg

Stop: 10:02 **AM** / PM Temp: °F Vacuum Level: 26 "of Hg

Comments: Infused in 17 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 2-B-S

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-B-S***

Data Sheet for Infusing Composite Structures

Date: 11/22/2010 **Shop Temperature:** °F

Name(s): Donald Soohey **Humidity:** %RH

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		CFM			√
2		E-LT 1603			√
3		E-LT 3610			√
4		E-LT 3610			√
5		H-100 (1.5)			√
6		E-LT 3610			√
7		E-LT 3610			√
8		E-LT 1603			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-B-S***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 11/22/2010 **Shop Temperature:** 68 °F

Name(s): Donald Soohey **Humidity:** %RH

Start: 7:55 **AM** / PM Vacuum Level: 29 ½ "of Hg
Stop: 8:10 **AM** / PM Vacuum Level: 28 ¾ "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

NO PIC AVAILABLE

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-B-S***

Data Sheet for
Infusing Composite Structures

INFUSION DATA

Date: 11/22/2010 **Shop Temperature:** 68 °F

Name(s): Donald Soohey **Humidity:** %RH

Infusion:

Start: 10:13 **AM** / PM Temp: 68 °F Vacuum Level: 28 ¼ "of Hg

Stop: 10:29 **AM** / PM Temp: °F Vacuum Level: 28 ¼ "of Hg

Comments: Infused in 16 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 2-M-C Redo

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-M-C***

Data Sheet for Infusing Composite Structures

Date: 1/04/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 26 %RH
Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

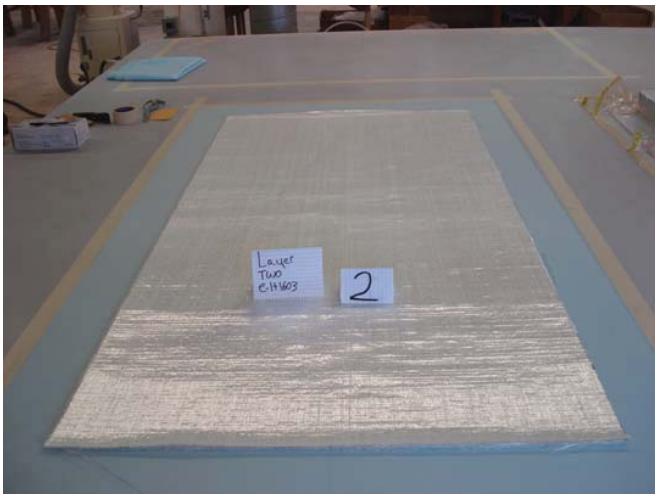
Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		CFM			√
2		E LT 1603			√
3		E LT 3610			√
4		E LT 3610			√
5		H100 (1.5)			√
6		E LT 3610			√
7		E LT 3610			√
8		E LT 1603			√

Core Thickness: 1.5”

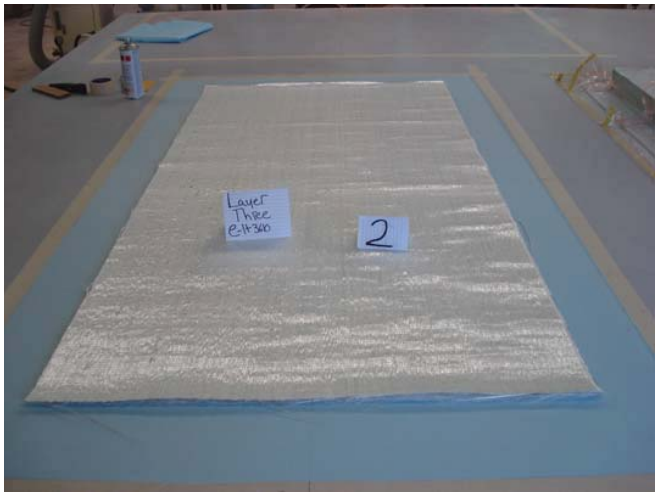
HODGDON SHIPBUILDING



1st Layer – CFM



2nd Layer – E-LT 1603



3rd Layer – E-LT 3610



4th Layer – E-LT 3610

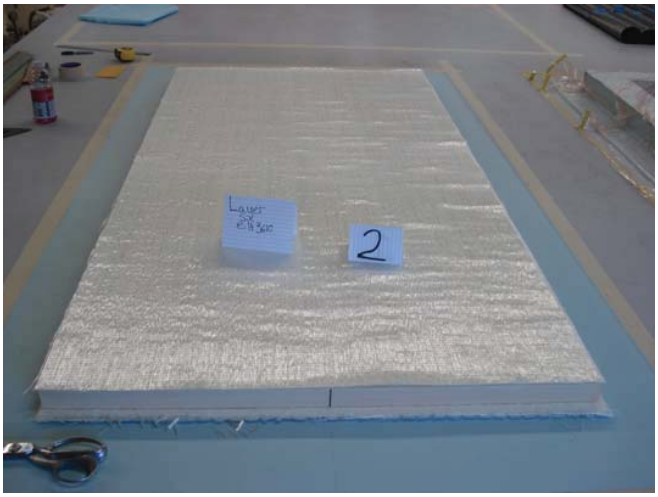
HODGDON SHIPBUILDING



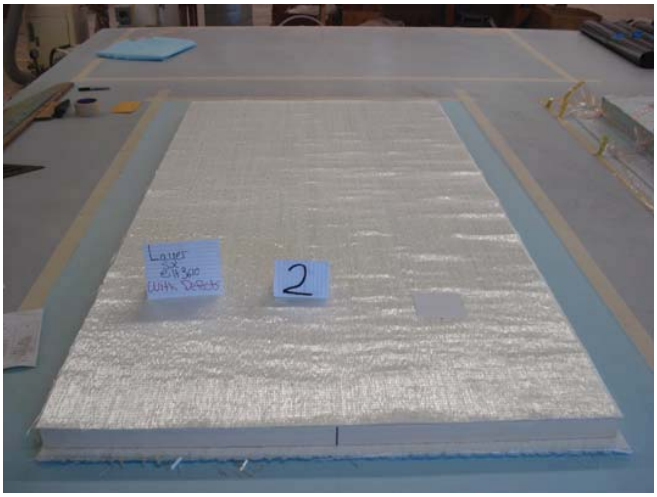
5th Layer – H100 (1.5) Core



5th Layer – H100 (1.5) Core with Defects

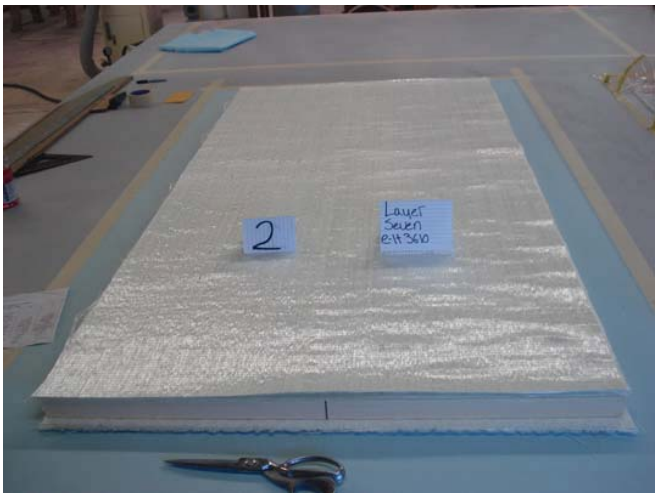


6th Layer – E-LT 3610

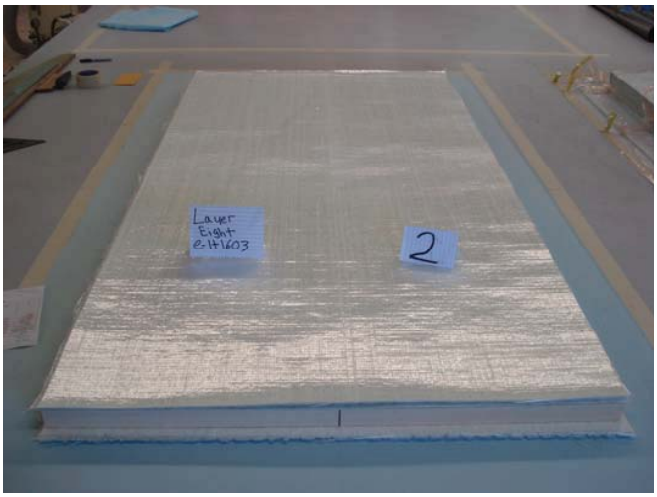


6th Layer – E-LT 3610 with Defects

HODGDON SHIPBUILDING



7th Layer – E-LT 3610



8th Layer – E-LT 1603

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-M-C***

Data Sheet for Infusing Composite Structures

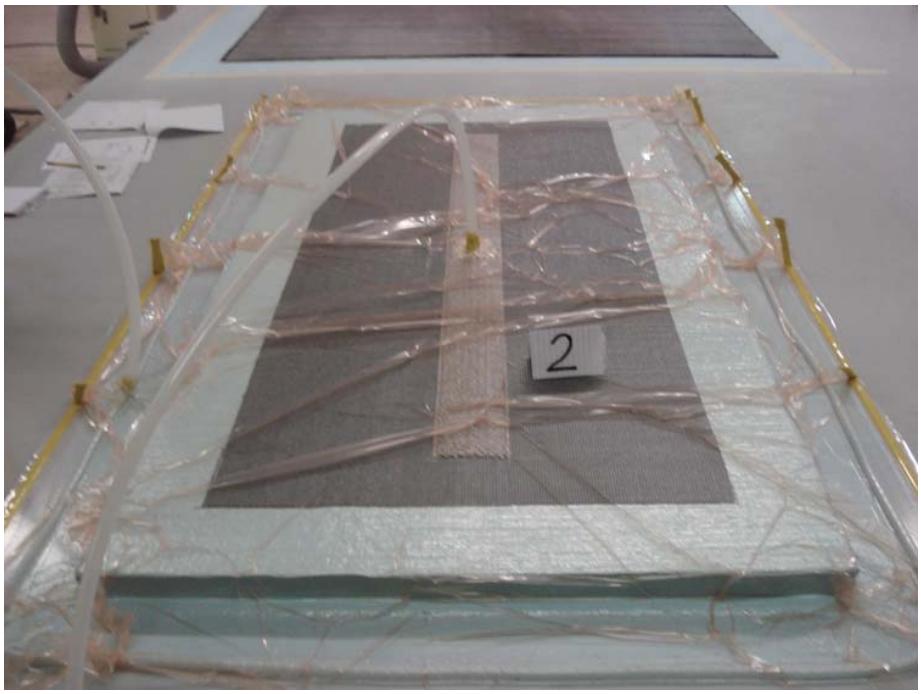
VACUUM INTEGRITY TEST POST LAY-UP

Date: 1/04/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 26 %RH
Sara Boston

Start: 12:05 AM / **PM** Vacuum Level: 28 ½ "of Hg
Stop: 12:20 AM / **PM** Vacuum Level: 28 ½ "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-M-C***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 1/04/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 26 %RH
Sara Boston

Infusion:

Start:	12:47 AM / **PM**	Temp:	71 °F	Vacuum Level:	28 ½ "of Hg
Stop:	1:21 AM / **PM**	Temp:	73 °F	Vacuum Level:	28 ½ "of Hg

Comments: Infused in 34 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 2-M-S Redo

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-M-S***

Data Sheet for Infusing Composite Structures

Date: 1/04/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 26 %RH
Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		CFM			√
2		E LT 1603			√
3		E LT 3610			√
4		E LT 3610			√
5		H100 (1.5)			√
6		E LT 3610			√
7		E LT 3610			√
8		E LT 1603			√

Core Thickness: 1.5”

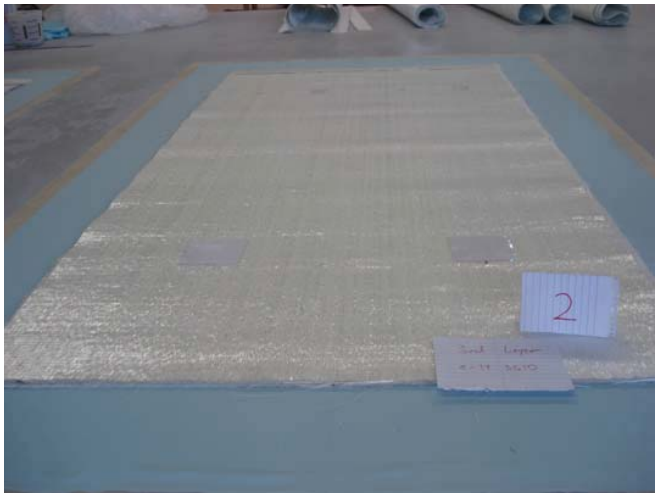
HODGDON SHIPBUILDING



1st Layer – CFM



2nd Layer – E-LT 1603



3rd Layer – E-LT 3610



Defects

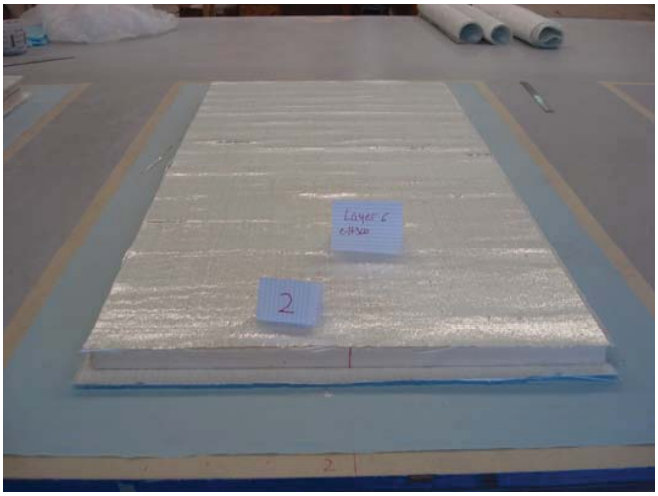
HODGDON SHIPBUILDING



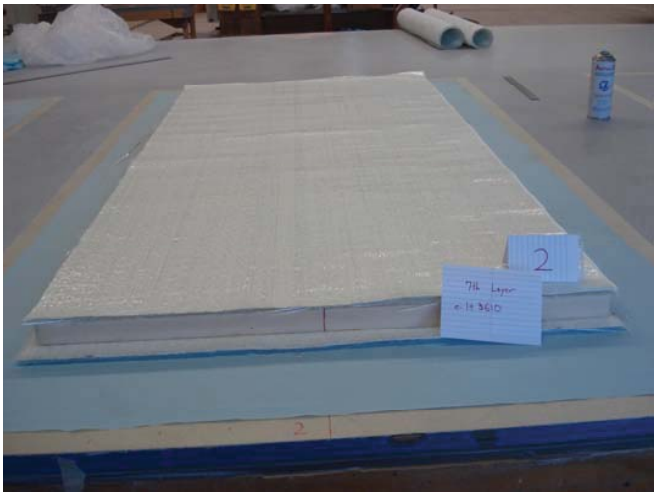
4th Layer – E-LT 3610



5th Layer – H100 (1.5) Core

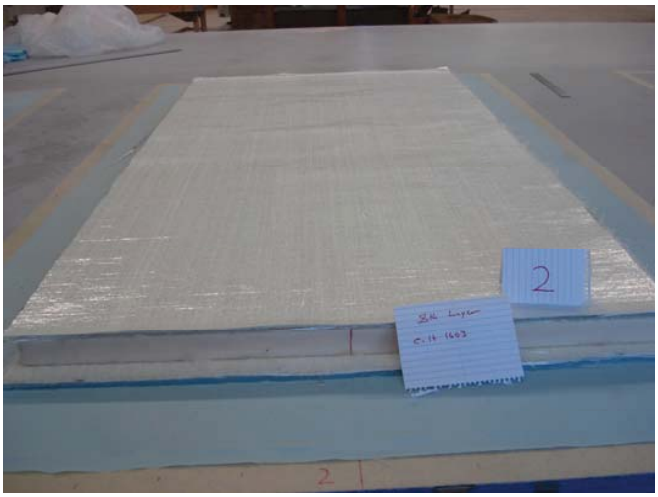


6th Layer – E-LT 3610



7th Layer – E-LT 3610

HODGDON SHIPBUILDING



8th Layer – E-LT 1603

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-M-S***

Data Sheet for Infusing Composite Structures

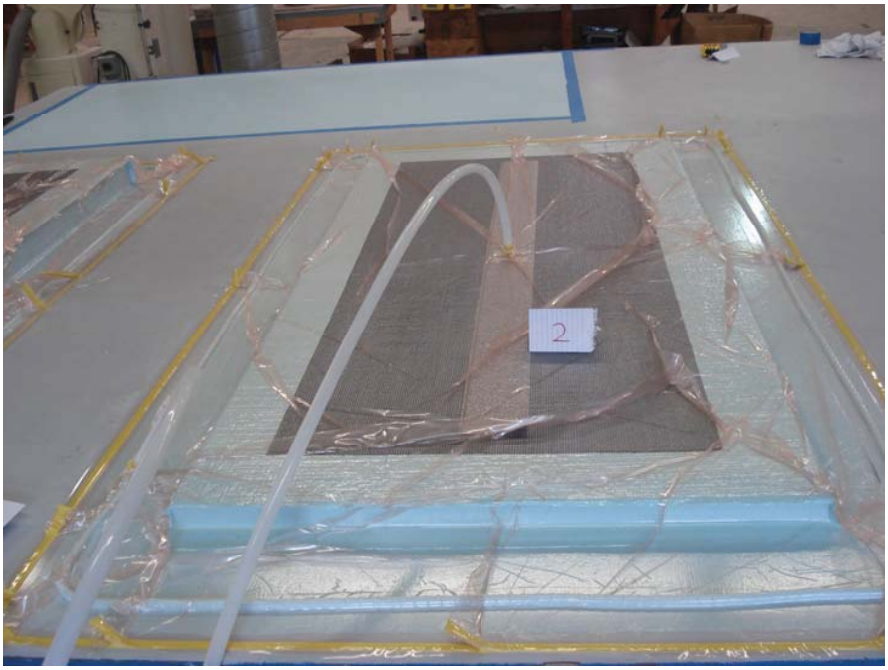
VACUUM INTEGRITY TEST POST LAY-UP

Date: 1/04/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 26 %RH
Sara Boston

Start: 12:05 AM / **PM** Vacuum Level: 28 ½ "of Hg
Stop: 12:20 AM / **PM** Vacuum Level: 28 ½ "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-M-S***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 1/04/2011 **Shop Temperature:** 71 °F

Name(s): Jason Wight **Humidity:** 26 %RH
Sara Boston

Infusion:

Start: 12:47 AM / **PM** Temp: 71 °F Vacuum Level: 28 ½ "of Hg
Stop: 1:21 AM / **PM** Temp: 73 °F Vacuum Level: 28 ½ "of Hg

Comments: Infused in 34 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 3-B

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-B***

Data Sheet for Infusing Composite Structures

Date: 10/06/2010 **Shop Temperature:** 72 °F

Name(s): Donald Soohey **Humidity:** 36.5 %RH
John Levins

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2	+/- 45	KBX 1308			√
3	+/- 45	CBX 1800			√
4	0/90	CLA 1812			√
5	+/- 45	CBX 1800			√
6		M100 (1.0)			√
7		CFM			√
8		M100 (1.0)			√
9	+/- 45	CBX 1200			√
10	0/90	CLA 1812			√
11		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-B***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 10/07/2010 **Shop Temperature:** 73 °F

Name(s): John Levins **Humidity:** 41.2 %RH

Start: 6:30 **AM** / PM Vacuum Level: 28 "of Hg
Stop: 6:45 **AM** / PM Vacuum Level: 27 ½ "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: 0632

Part Number: 3-B

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 10/07/2010 **Shop Temperature:** 72.5 °F

Name(s): John Levins **Humidity:** 41.2 %RH
Donald Soohey

Infusion:

Start: 7:50 **AM** / PM Temp: 73.5 °F Vacuum Level: 28 "of Hg
Stop: 8:30 **AM** / PM Temp: 85.8 °F Vacuum Level: 28 "of Hg

Comments: Infused in 50 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 3-B-C

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-B-C***

Data Sheet for Infusing Composite Structures

Date: 11/04/2010 **Shop Temperature:** 72.5 °F

Name(s): Donald Soohey **Humidity:** 27 %RH

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		KBX 1308			√
3		CBX 1800			√
4		CLA 1812			√
5		CBX 1800			√
6		M100 (1.0)			√
7		CFM			√
8		M100 (1.0)			√
9		CBX 1200			√
10		CLA 1812			√
11		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-B-C***

Data Sheet for Infusing Composite Structures

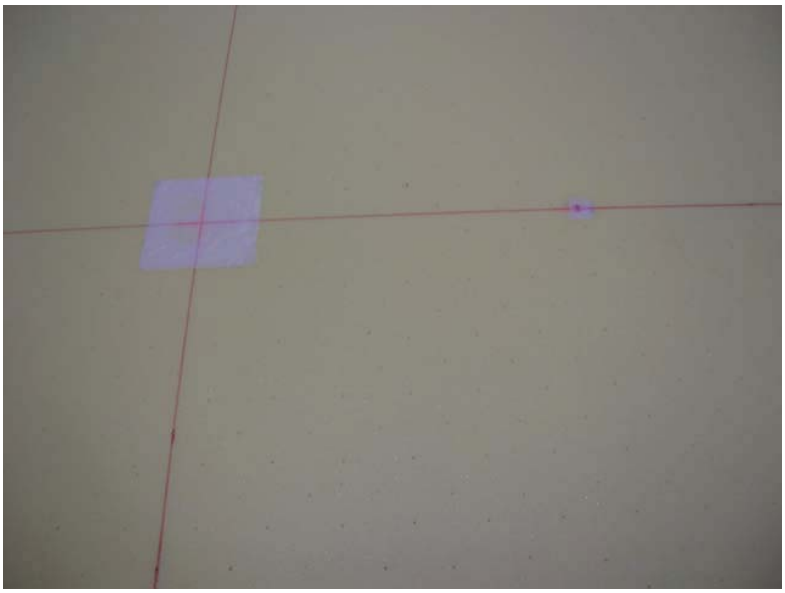
VACUUM INTEGRITY TEST POST LAY-UP

Date: 11/04/2010 **Shop Temperature:** 72.5 °F

Name(s): John Levins **Humidity:** 27 %RH

Start: 11:00 AM / **PM** Vacuum Level: 30 "of Hg
Stop: 11:15 AM / **PM** Vacuum Level: 30 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



Picture of Panel 3-B-C showing defects

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-B-C***

Data Sheet for
Infusing Composite Structures

INFUSION DATA

Date: 11/04/2010 **Shop Temperature:** 62.5 °F

Name(s): John Levins **Humidity:** %RH
Donald Soohey

Infusion: Resin Temp: 69 °F
Start: 12:28 AM / **PM** Temp: 72.5 °F Vacuum Level: 30 "of Hg
Stop: 1:15 AM / **PM** Temp: 72.5 °F Vacuum Level: 30 "of Hg

Comments: Infused in 43 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: ***0632***

Part Number: ***3-B-S***

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-B-S***

Data Sheet for Infusing Composite Structures

Date: 11/04/2010 **Shop Temperature:** 72.5 °F

Name(s): Donald Soohey **Humidity:** %RH

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		KBX 1308			√
3		CBX 1800			√
4		CLA 1812			√
5		CBX 1800			√
6		M100 (1.0)			√
7		CFM			√
8		M100 (1.0)			√
9		CBX 1200			√
10		CLA 1812			√
11		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-B-S***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 11/04/2010 **Shop Temperature:** 72.5 °F

Name(s): John Levins **Humidity:** %RH

Start: 11:00 AM / **PM** Vacuum Level: 28 ½ "of Hg
Stop: 11:15 AM / **PM** Vacuum Level: 28 ¼ "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



Picture of lay up

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-B-S***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 11/04/2010 **Shop Temperature:** 72.5 °F

Name(s): John Levins **Humidity:** %RH
Donald Soohey

Infusion: Resin: 71.6
Start: 1:20 AM / **PM** Temp: 72.5 °F Vacuum Level: 28 ½ "of Hg
Stop: 2:08 AM / **PM** Temp: 73 °F Vacuum Level: 28 ½ "of Hg

Comments: Infused in 48 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 3-M-C Redo

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-M-C***

Data Sheet for Infusing Composite Structures

Date: 1/05/2011 **Shop Temperature:** 68.2 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

LAY-UP EXAMINATION

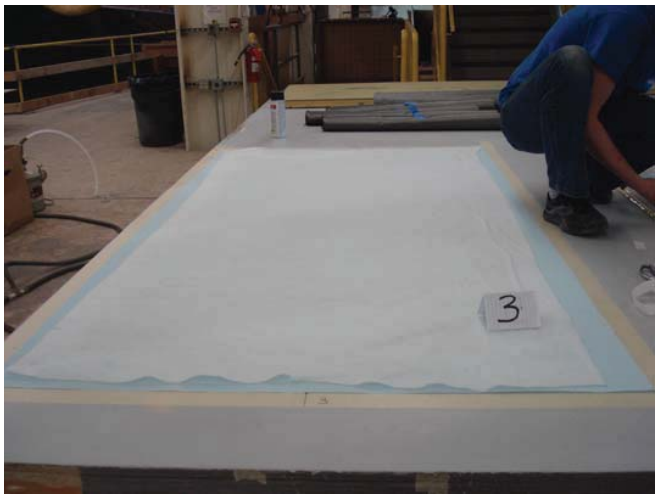
Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		KBX 1308			√
3		CBX 1800			√
4		CLA 1812			√
5		CBX 1800			√
6		M100 (1.0)			√
7		CFM			√
8		M100 (1.0)			√
9		CBX 1200			√
10		CLA 1812			√
11		CBX 1200			√

Core Thickness: __

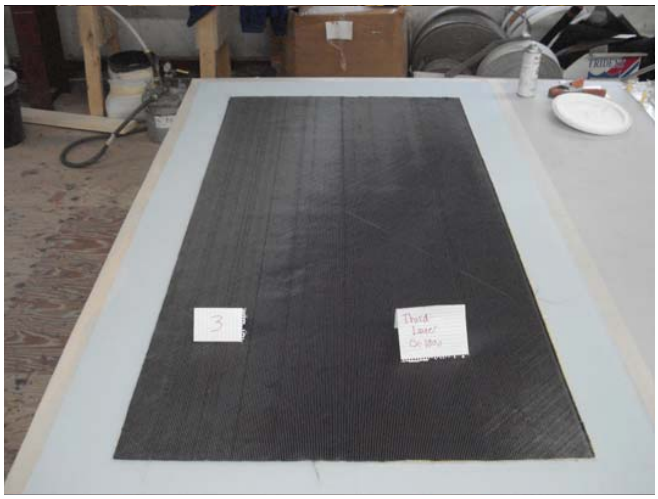
HODGDON SHIPBUILDING



1st Layer – Veil



2nd Layer – KBX 1308

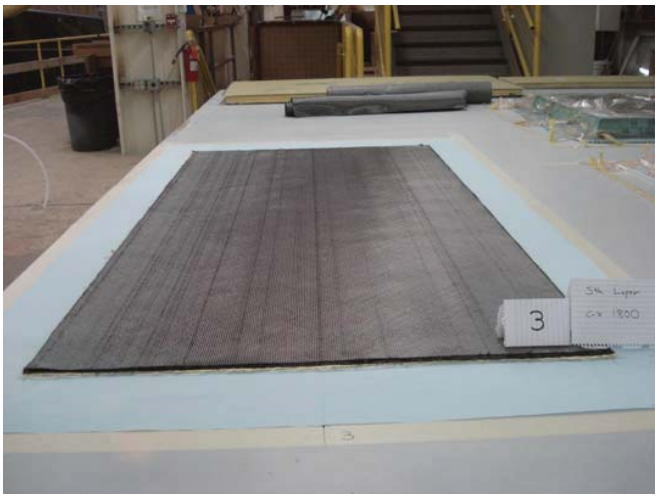


3rd Layer – CBX 1800



4th Layer – CLA 1812

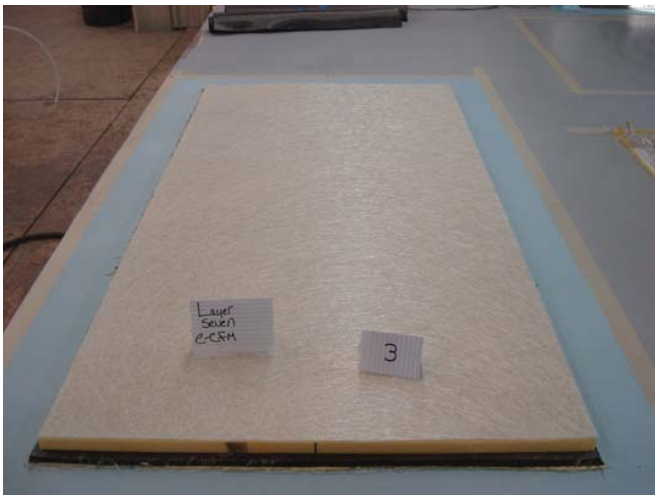
HODGDON SHIPBUILDING



5th Layer – CBX 1800



6th Layer – H100 (1.0) Core

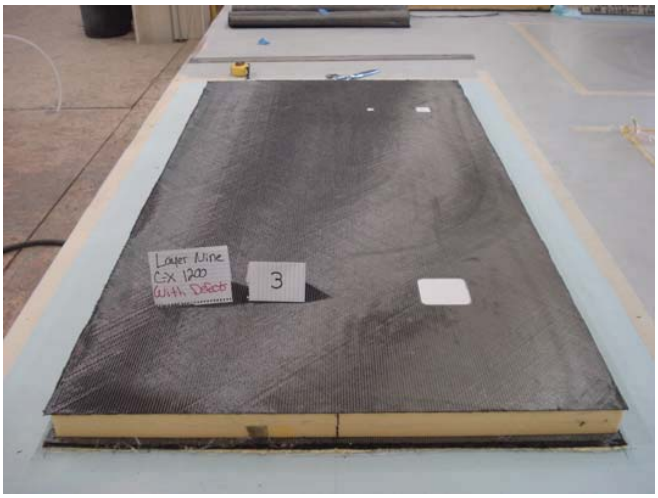


7th Layer – CFM



8th Layer – H100 (1.0) Core

HODGDON SHIPBUILDING



9th Layer – CBX 1200



10th Layer – CLA 1812



11th Layer – CBX 1200

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-M-C***

Data Sheet for Infusing Composite Structures

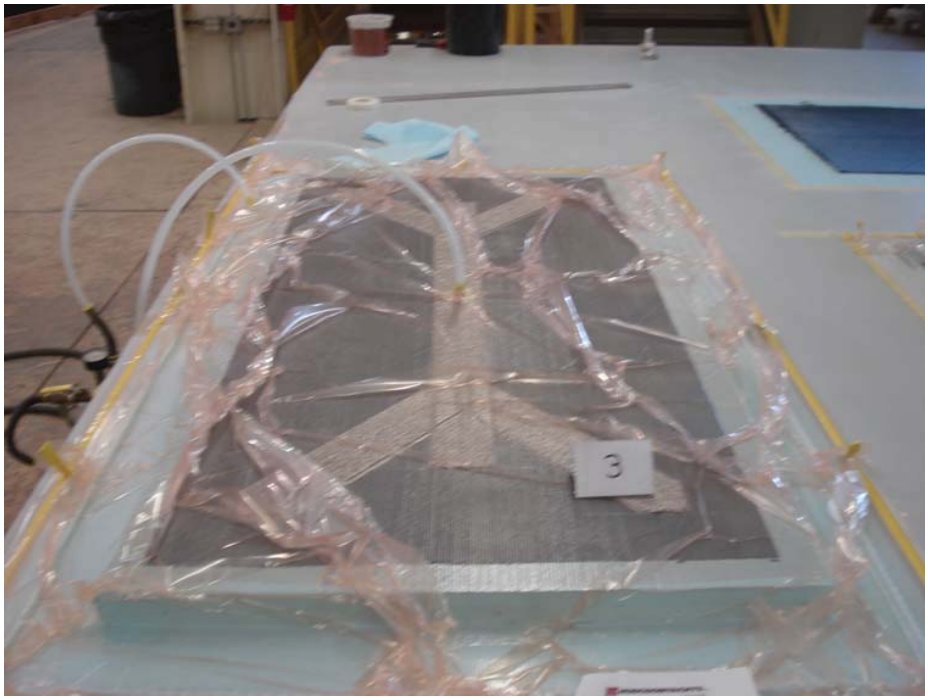
VACUUM INTEGRITY TEST POST LAY-UP

Date: 1/05/2011 **Shop Temperature:** 68.3 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

Start: 12:10 AM / **PM** Vacuum Level: 30 "of Hg
Stop: 12:25 AM / **PM** Vacuum Level: 30 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-M-C***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 1/05/2011 **Shop Temperature:** 68.4 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

Infusion: Resin Temp: 66 °F
Start: 12:55 AM / **PM** Temp: 69 °F Vacuum Level: 30 "of Hg
Stop: 2:00 AM / **PM** Temp: 72 °F Vacuum Level: 30 "of Hg

Comments: Infused in 1 Hour 5 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 3-M-S

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-M-S***

Data Sheet for Infusing Composite Structures

Date: 10/10/2010 **Shop Temperature:** 74 °F

Name(s): John Levins **Humidity:** 26 %RH
Kyle Macklin

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		KBX 1308			√
3		CBX 1800			√
4		CLA 1812			√
5		CBX 1800			√
6		M100 (1.0)			√
7		CFM			√
8		M100 (1.0)			√
9		CBX 1200			√
10		CLA 1812			√
11		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-M-S***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 10/11/2010 **Shop Temperature:** 74 °F

Name(s): Jason Wight **Humidity:** 27.1 %RH
Sara Boston

Start: 3:45 AM / **PM** Vacuum Level: 29 "of Hg
Stop: 4:00 AM / **PM** Vacuum Level: 29 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-M-S***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 10/11/2010 **Shop Temperature:** 77 °F

Name(s): John Levins **Humidity:** 27.1 %RH
Kyle Macklin

Infusion:

Start: 4:15 AM / **PM** Temp: 78 °F Vacuum Level: 29 "of Hg
Stop: 4:55 AM / **PM** Temp: °F Vacuum Level: 29 "of Hg

Comments: Infused in 40 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 4-B

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-B***

Data Sheet for Infusing Composite Structures

Date: 10/06/2010 **Shop Temperature:** 73 °F

Name(s): Donald Soohey **Humidity:** 36.5 %RH
Rob Osman

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		CBX 1800			√
3		CLA 1812			√
4		CBX 1200			√
5		M80 (1.0)			√
6		CBX 1200			√
7		CLA 1812			√
8		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-B***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 10/07/2010 **Shop Temperature:** 74 °F

Name(s): Chad Jones **Humidity:** 41.4 %RH

Start: 6:30 **AM** / PM Vacuum Level: 28 "of Hg
Stop: 6:45 **AM** / PM Vacuum Level: 27.5 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-B***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 10/07/2010 **Shop Temperature:** 73 °F

Name(s): John Levins **Humidity:** 41 %RH
Rob Osman

Infusion:

Start:	8:35 **AM** / PM	Temp:	74.4 °F	Vacuum Level:	28 "of Hg
Stop:	9:05 **AM** / PM	Temp:	80 °F	Vacuum Level:	28 "of Hg

Comments: Infused in 30 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 4-B-C

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-B-C***

Data Sheet for Infusing Composite Structures

Date: 11/01/2010 **Shop Temperature:** °F

Name(s): Donald Soohey **Humidity:** %RH

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		CBX 1800			√
3		CLA 1812			√
4		CBX 1200			√
5		M80 (1.0)			√
6		CBX 1200			√
7		CLA 1812			√
8		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-B-C***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 11/02/2010 **Shop Temperature:** 69 °F

Name(s): Chad Jones **Humidity:** %RH

Start: 6:45 **AM** / PM Vacuum Level: 28.5 "of Hg
Stop: 7:00 **AM** / PM Vacuum Level: 28.5 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-B-C***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 11/02/2010 **Shop Temperature:** 69 °F

Name(s): Donald Soohey **Humidity:** %RH

Infusion:

Start: 7:03 AM / **PM** Temp: 69 °F Vacuum Level: 28.5 "of Hg

Stop: 7:56 AM / **PM** Temp: 72 °F Vacuum Level: 28.5 "of Hg

Comments: Infused in 53 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 4-B-S

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-B-S***

Data Sheet for Infusing Composite Structures

Date: 10/28/2010 **Shop Temperature:** 72.5 °F

Name(s): Donald Soohey **Humidity:** %RH

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		CBX 1800			√
3		CLA 1812			√
4		CBX 1200			√
5		M80 (1.0)			√
6		CBX 1200			√
7		CLA 1812			√
8		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-B-S***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 10/28/2010 **Shop Temperature:** 72.9 °F

Name(s): Donald Soohey **Humidity:** %RH

Start: 12:00 AM / **PM** Vacuum Level: 29 ½ "of Hg
Stop: 12:15 AM / **PM** Vacuum Level: 29 ¾ "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-B-S***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 10/28/2010 **Shop Temperature:** 72.9 °F

Name(s): Donald Soohey **Humidity:** %RH

Infusion: Resin: 71

Start: 12:28 AM / **PM** Temp: 72 °F Vacuum Level: 29.5 "of Hg

Stop: 1:10 AM / **PM** Temp: 77.9 °F Vacuum Level: 29.5 "of Hg

Comments: Infused in 42 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 4-M-C Redo

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-M-C***

Data Sheet for Infusing Composite Structures

Date: 1/05/2011 **Shop Temperature:** 68.2 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

LAY-UP EXAMINATION

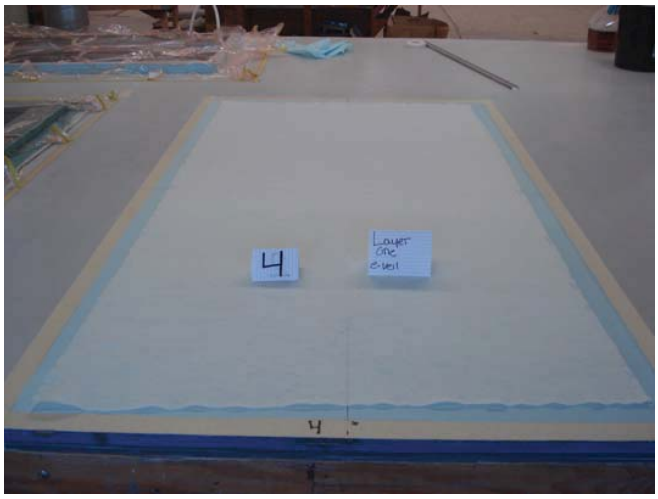
Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

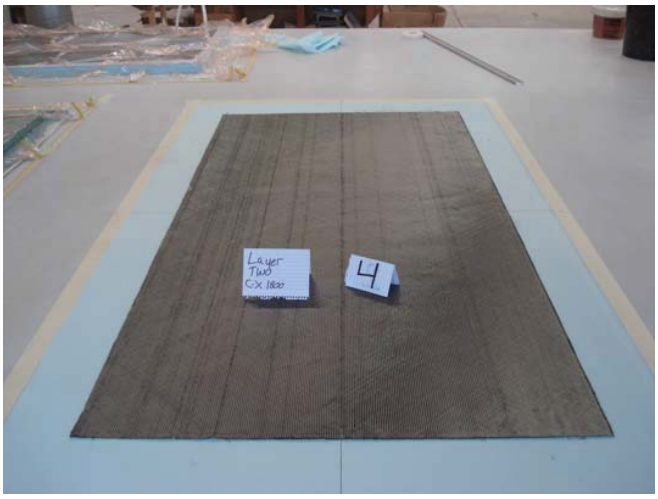
Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		CBX 1800			√
3		CLA 1812			√
4		CBX 1200			√
5		M80 (1.0)			√
6		CBX 1200			√
7		CLA 1812			√
8		CBX 1200			√

Core Thickness: __

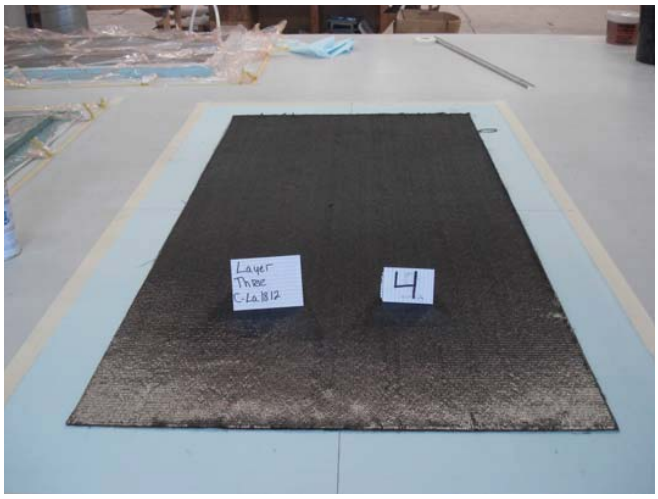
HODGDON SHIPBUILDING



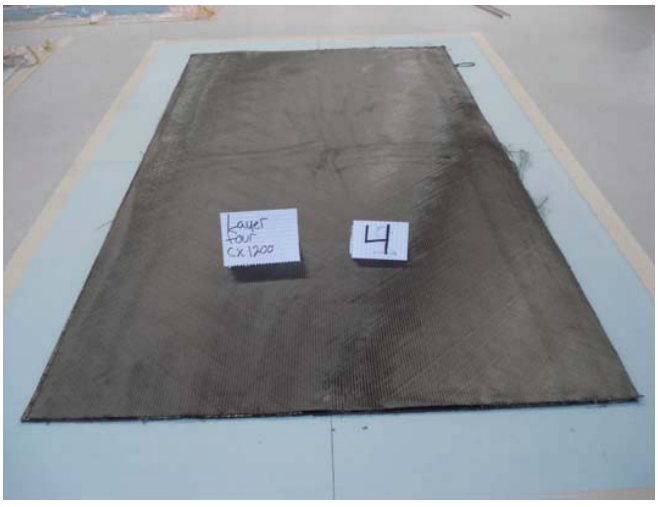
1st Layer – Veil



2nd Layer – CBX 1800

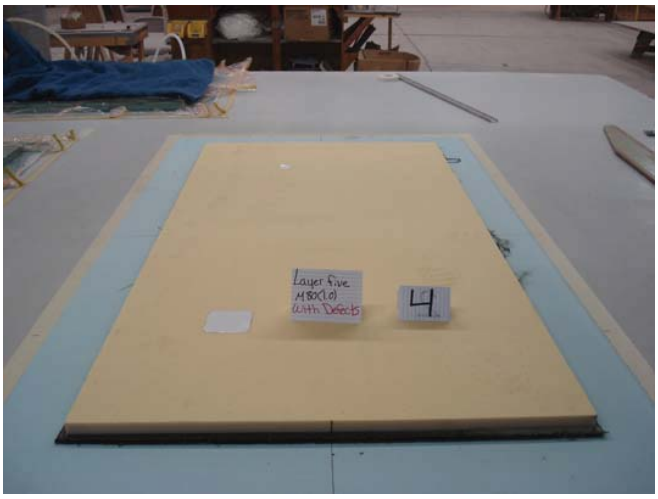


3rd Layer – CLA 1812

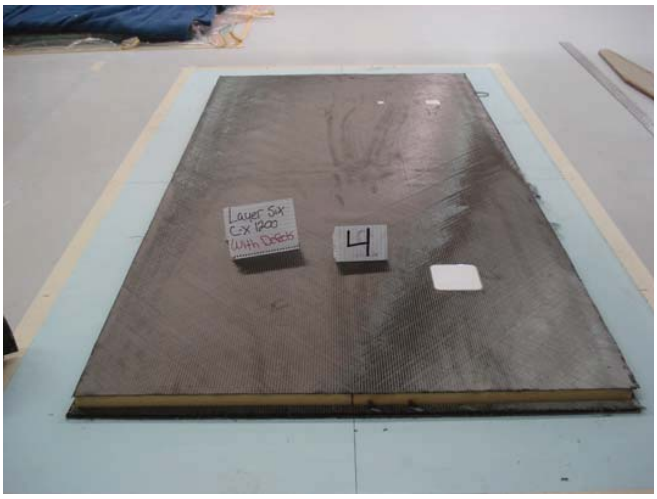


4th Layer – CBX 1200

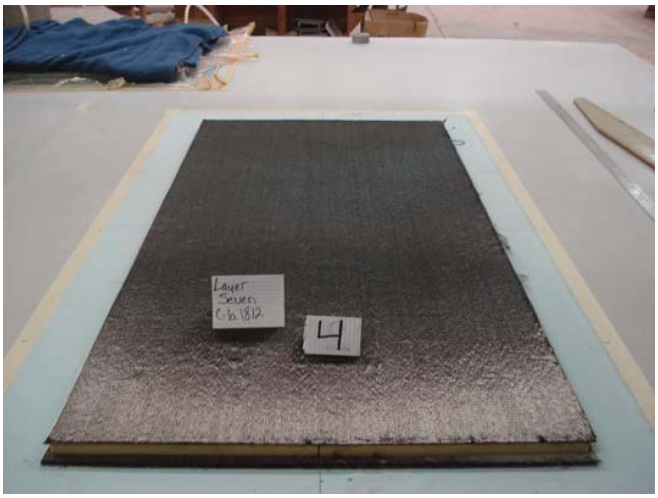
HODGDON SHIPBUILDING



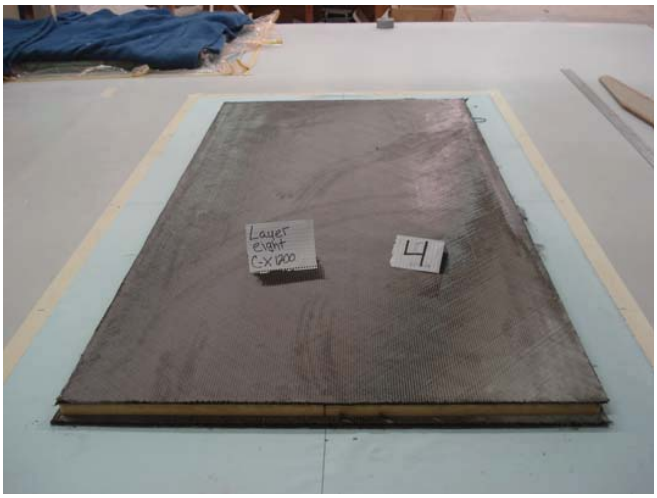
5th Layer – M80 (1.0) Core



6th Layer – CBX 1200



7th Layer – CLA 1812



8th Layer – CBX 1200

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-M-C***

Data Sheet for Infusing Composite Structures

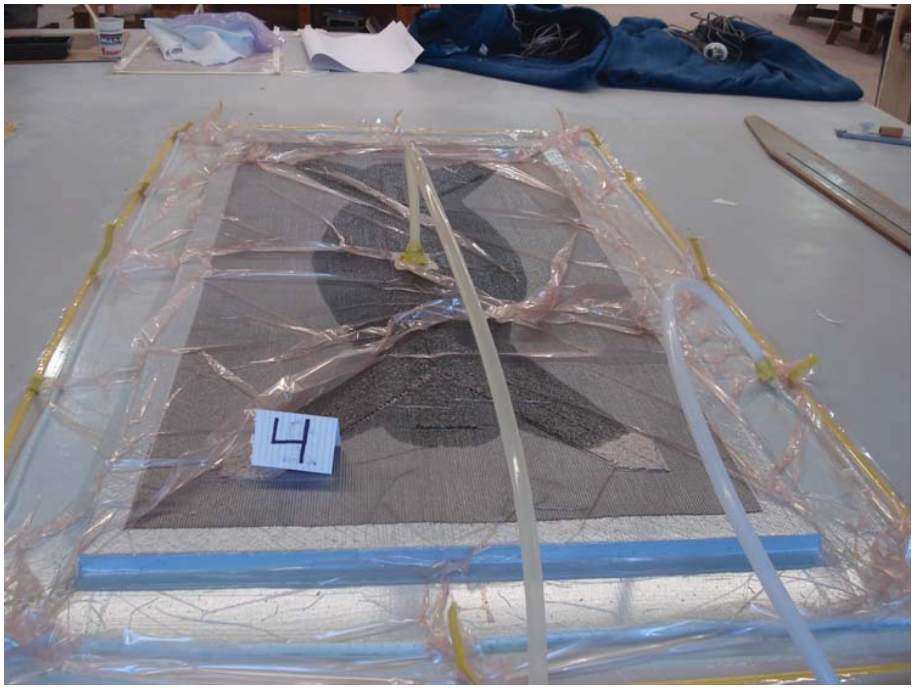
VACUUM INTEGRITY TEST POST LAY-UP

Date: 1/05/2011 **Shop Temperature:** 68.2 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

Start: 12:10 AM / **PM** Vacuum Level: 28 "of Hg
Stop: 12:25 AM / **PM** Vacuum Level: 28 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-M-C***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 1/05/2011 **Shop Temperature:** 68.4 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

Infusion: Resin Temp: 68 °F
Start: 12:33 AM / **PM** Temp: 69 °F Vacuum Level: 28 "of Hg
Stop: 1:13 AM / **PM** Temp: 71.5 °F Vacuum Level: 28 "of Hg

Comments: Infused in 50 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 4-M-S Redo

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-M-S***

Data Sheet for Infusing Composite Structures

Date: 1/05/2011 **Shop Temperature:** 68.2 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		CBX 1800			√
3		CLA 1812			√
4		CBX 1200			√
5		M80 (1.0)			√
6		CBX 1200			√
7		CLA 1812			√
8		CBX 1200			√

Core Thickness: __

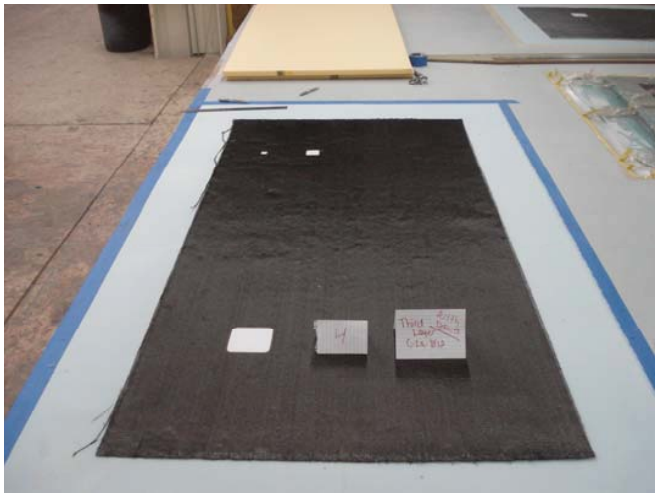
HODGDON SHIPBUILDING



1st Layer – Veil



2nd Layer – CBX 1800



3rd Layer – CLA 1812



4th Layer – CBX 1200

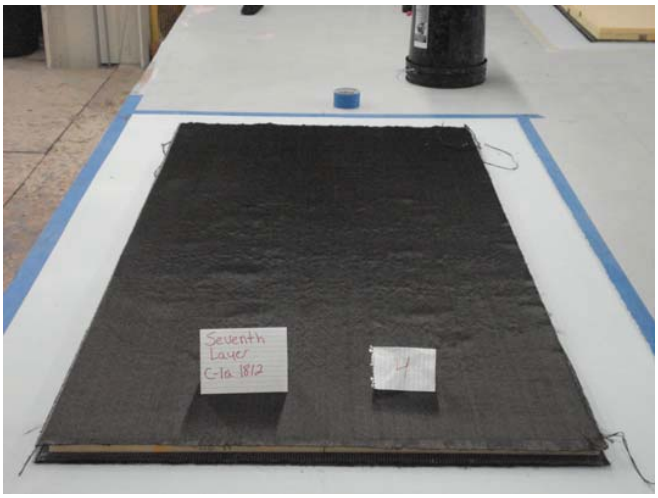
HODGDON SHIPBUILDING



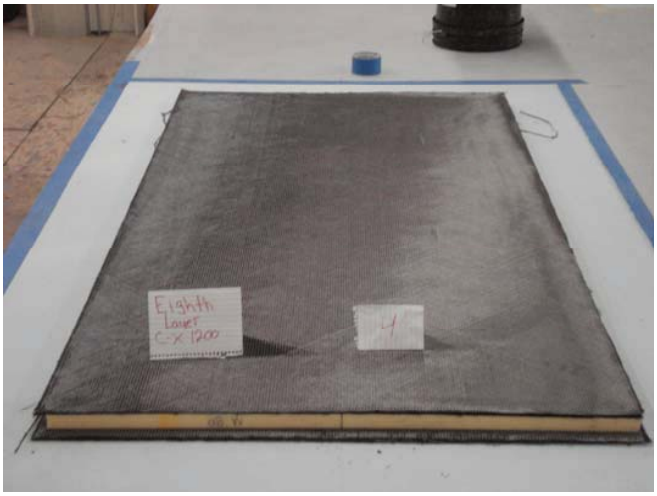
5th Layer – M80 (1.0) Core



6th Layer – CBX 1200



7th Layer – CLA 1812



8th Layer – CBX 1200

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-M-S***

Data Sheet for Infusing Composite Structures

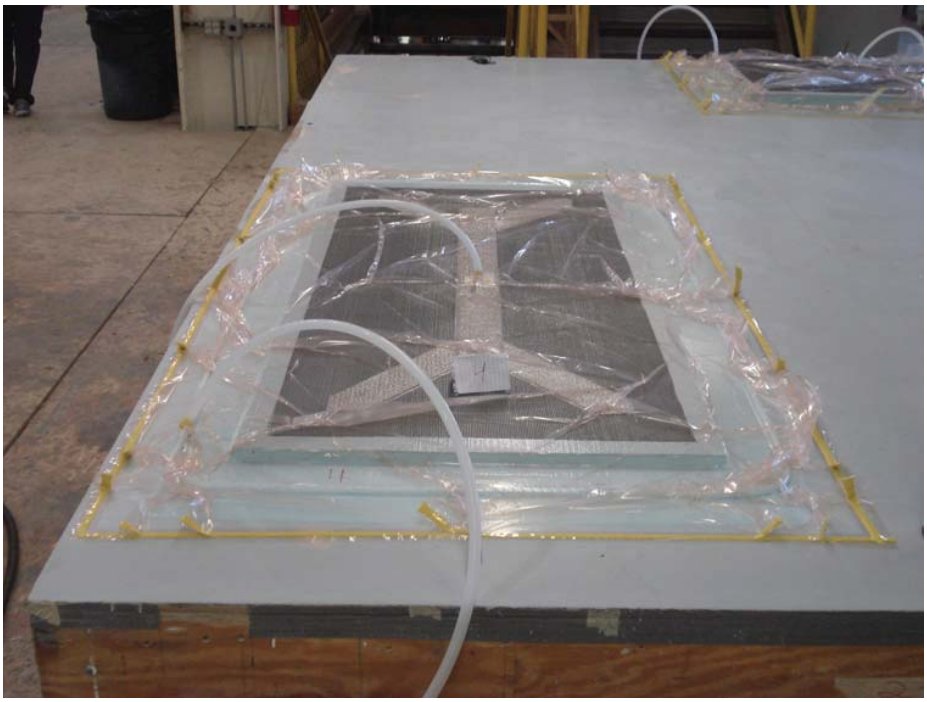
VACUUM INTEGRITY TEST POST LAY-UP

Date: 1/05/2011 **Shop Temperature:** 68.2 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

Start: 12:10 AM / **PM** Vacuum Level: 28 "of Hg
Stop: 12:25 AM / **PM** Vacuum Level: 28 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-M-S***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 1/05/2011 **Shop Temperature:** 68.4 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

Infusion: Resin Temp: 68 °F
Start: 12:33 AM / **PM** Temp: 69 °F Vacuum Level: 28 "of Hg
Stop: 1:13 AM / **PM** Temp: 71.5 °F Vacuum Level: 28 "of Hg

Comments: Infused in 50 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 5-B

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-B***

Data Sheet for Infusing Composite Structures

Date: 10/07/2010 **Shop Temperature:** 73 °F

Name(s): Rob Osman **Humidity:** 41 %RH
John Levins

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		KBX 1308			√
3		KBX 1308			√(-45)
4		KBX 1308			√(+45)
5		ECFM			√
6		M80 (1.5)			√
7		CLT 1800			√
8		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-B***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 10/08/2010 **Shop Temperature:** 74 °F

Name(s): John Levins **Humidity:** 30.6 %RH

Start: 8:45 **AM** / PM Vacuum Level: 28 "of Hg
Stop: 9:00 **AM** / PM Vacuum Level: 28 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-B***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 10/08/2010 **Shop Temperature:** 74 °F

Name(s): John Levins **Humidity:** 30.6 %RH
Rob Osman

Infusion:

Start:	10:05 **AM** / PM	Temp:	74 °F	Vacuum Level:	28 "of Hg
Stop:	10:35 **AM** / PM	Temp:	76 °F	Vacuum Level:	28 "of Hg

Comments: Infused in 30 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 5-B-C

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-B-C***

Data Sheet for Infusing Composite Structures

Date: 11/08/2010 **Shop Temperature:** 71.3 °F

Name(s): John Levins **Humidity:** %RH
Donald Soohey

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		KBX 1308			√
3		KBX 1308			√(-45)
4		KBX 1308			√(+45)
5		ECFM			√
6		M80 (1.5)			√
7		CLT 1800			√
8		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-B-C***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 11/09/2010 **Shop Temperature:** 73 °F

Name(s): Chad jones **Humidity:** %RH

Start: 10:25 **AM** / PM Vacuum Level: 28 "of Hg
Stop: 10:40 **AM** / PM Vacuum Level: 27.5 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-B-C***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 11/09/2011 **Shop Temperature:** 74 °F

Name(s): John Levins **Humidity:** 25 %RH
Donald Soohey

Infusion:

Start:	10:45 **AM** / PM	Temp:	74 °F	Vacuum Level:	28 "of Hg
Stop:	11:23 **AM** / PM	Temp:	77 °F	Vacuum Level:	28 "of Hg

Comments: Infused in 38 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 5-B-S

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-B-S***

Data Sheet for Infusing Composite Structures

Date: 11/08/2010 **Shop Temperature:** 71.3 °F

Name(s): John Levins **Humidity:** %RH
Donald Soohey

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		KBX 1308			√
3		KBX 1308			√(-45)
4		KBX 1308			√(+45)
5		ECFM			√
6		M80 (1.5)			√
7		CLT 1800			√
8		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-B-S***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 11/09/2010 **Shop Temperature:** 73 °F

Name(s): Chad Jones **Humidity:** %RH

Start: 10:25 **AM** / PM Vacuum Level: 30 "of Hg
Stop: 10:40 **AM** / PM Vacuum Level: 29.5 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-B-S***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 11/09/2011 **Shop Temperature:** 74 °F

Name(s): John Levins **Humidity:** %RH
Donald Soohey

Infusion:

Start: 12:05 **AM** / PM Temp: 75 °F Vacuum Level: 30 "of Hg
Stop: 12:42 **AM** / PM Temp: 79 °F Vacuum Level: 30 "of Hg

Comments: Infused in 37 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 5-M-C

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-M-C***

Data Sheet for Infusing Composite Structures

Date: 1/07/2011 **Shop Temperature:** 63.7 °F

Name(s): Sara Boston **Humidity:** 25 %RH

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		KBX 1308			√(-45)
3		KBX 1308			√(+45)
4		KBX 1308			√
5		ECFM			√
6		M80 (1.5)			√
7		CLT 1800			√
8		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-M-C***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 1/07/2011 **Shop Temperature:** 63.7 °F

Name(s): Sara Boston **Humidity:** 25 %RH

Start: 9:15 **AM** / PM Vacuum Level: 28 "of Hg
Stop: 9:30 **AM** / PM Vacuum Level: 27.5 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

NO PIC AVAILABLE

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-M-C***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 1/07/2011 **Shop Temperature:** 63.7 °F

Name(s): Sara Boston **Humidity:** 25 %RH

Infusion: Resin: 79

Start: 9:42 **AM** / PM Temp: 68 °F Vacuum Level: 28 "of Hg

Stop: 10:20 **AM** / PM Temp: °F Vacuum Level: 28 "of Hg

Comments: Infused in 38 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 5-M-S

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-M-S***

Data Sheet for Infusing Composite Structures

Date: 1/07/2011 **Shop Temperature:** 63.7 °F

Name(s): Sara Boston **Humidity:** 25 %RH

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		KBX 1308			√(-45)
3		KBX 1308			√(+45)
4		KBX 1308			√
5		ECFM			√
6		M80 (1.5)			√
7		CLT 1800			√
8		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-M-S***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 1/07/2011 **Shop Temperature:** 63.7 °F

Name(s): Sara Boston **Humidity:** 25 %RH

Start: 9:15 **AM** / PM Vacuum Level: 28 "of Hg
Stop: 9:30 **AM** / PM Vacuum Level: 27.5 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

NO PIC AVAILABLE

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-M-S***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 1/07/2011 **Shop Temperature:** 63.7 °F

Name(s): Sara Boston **Humidity:** 25 %RH

Infusion: Resin: 79

Start: 9:42 **AM** / PM Temp: 68 °F Vacuum Level: 28 "of Hg

Stop: 10:20 **AM** / PM Temp: °F Vacuum Level: 28 "of Hg

Comments: Infused in 38 minutes

Original Panel Infusion Sheets

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 1-M-C

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-M-C***

Data Sheet for Infusing Composite Structures

Date: 10/20/2010 **Shop Temperature:** 72 °F

Name(s): John Levins **Humidity:** 28.9 %RH
Donald Soohey

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		CFM			√
2		E LT 1603			√
3		E LT 2415			√
4		E LT 3610			√
5		E LT 3610			√
6		H130 (1.5)			√
7		CFM			√
8		H130 (1.5)			√
9		E LT 3610			√
10		E LT 3610			√
11		E LT 2415			√
12		E LT 1603			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-M-C***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 10/22/2010 **Shop Temperature:** 72 °F

Name(s): Skip Orne **Humidity:** 25.4 %RH

Start: 11:15 **AM** / PM Vacuum Level: 27 "of Hg
Stop: 11:30 **AM** / PM Vacuum Level: 27 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

NO PIC AVAILABLE

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-M-C***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 10/22/2010 **Shop Temperature:** 72 °F

Name(s): Skip Orne **Humidity:** 25.4 %RH

Infusion:

Start: 1:30 AM / **PM** Temp: 72 °F Vacuum Level: 27 "of Hg

Stop: 1:47 AM / **PM** Temp: 72 °F Vacuum Level: 27 "of Hg

Comments: Infused in 17 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 1-M-S

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-M-S***

Data Sheet for Infusing Composite Structures

Date: 10/18/2010 **Shop Temperature:** 74 °F

Name(s): John Levins **Humidity:** 26.4 %RH
Donald Soohey

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		CFM			√
2		E LT 1603			√
3		E LT 2415			√
4		E LT 3610			√
5		E LT 3610			√
6		H130 (1.5)			√
7		CFM			√
8		H130 (1.5)			√
9		E LT 3610			√
10		E LT 3610			√
11		E LT 2415			√
12		E LT 1603			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-M-S***

Data Sheet for Infusing Composite Structures

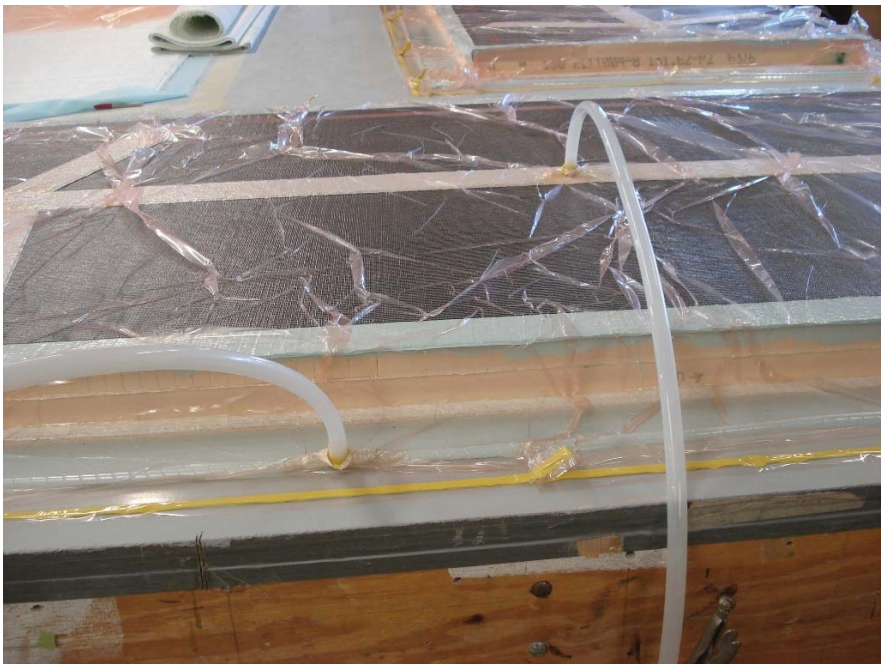
VACUUM INTEGRITY TEST POST LAY-UP

Date: 10/19/2010 **Shop Temperature:** 74 °F

Name(s): John Levins **Humidity:** 25.9 %RH

Start: 12:00 AM / **PM** Vacuum Level: 28 "of Hg
Stop: 12:15 AM / **PM** Vacuum Level: 28 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***1-M-S***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 10/19/2010 **Shop Temperature:** 74 °F

Name(s): John Levins **Humidity:** 25.9 %RH
Donald Soohey

Infusion:

Start: 2:00 AM / **PM** Temp: 74 °F Vacuum Level: 28 "of Hg
Stop: 2:20 AM / **PM** Temp: °F Vacuum Level: 28 "of Hg

Comments: Infused in 20 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 2-M-C

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-M-C***

Data Sheet for Infusing Composite Structures

Date: 11/22/2010 **Shop Temperature:** °F

Name(s): Donald Soohey **Humidity:** %RH

LAY-UP EXAMINATION

Panel Lay-Up:

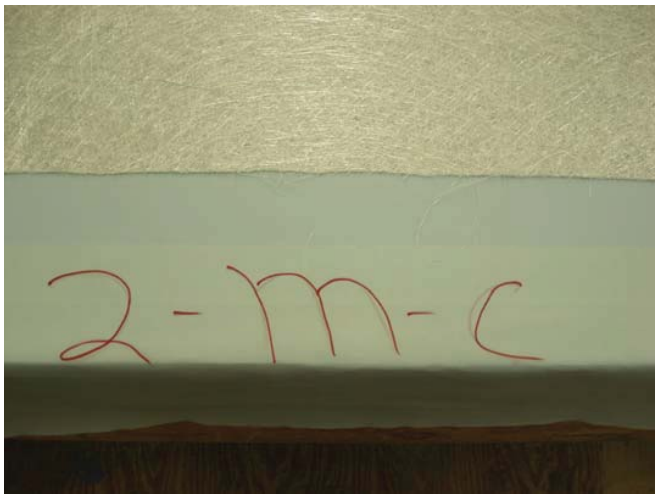
Ply 1 is ply closest to table/mold

Add sheets if necessary

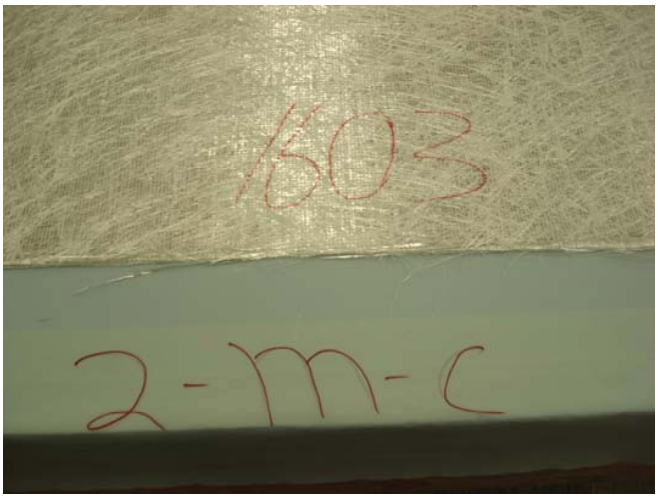
Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		CFM			√
2		E LT 1603			√
3		E LT 3610			√
4		E LT 3610			√
5		H100 (1.5)			√
6		E LT 3610			√
7		E LT 3610			√
8		E LT 1603			√

Core Thickness: 1.5”

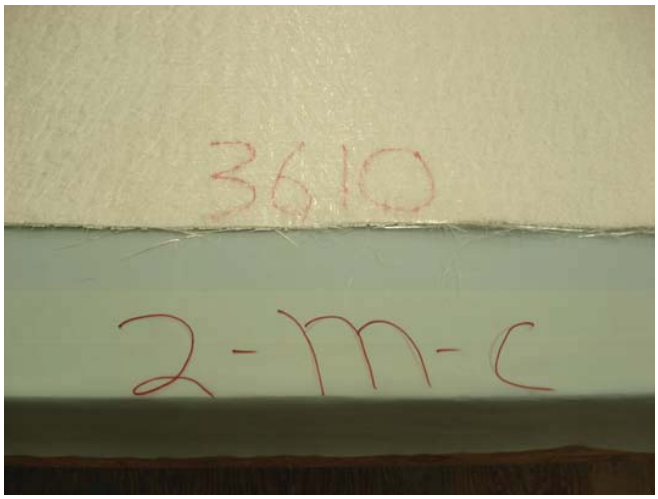
HODGDON SHIPBUILDING



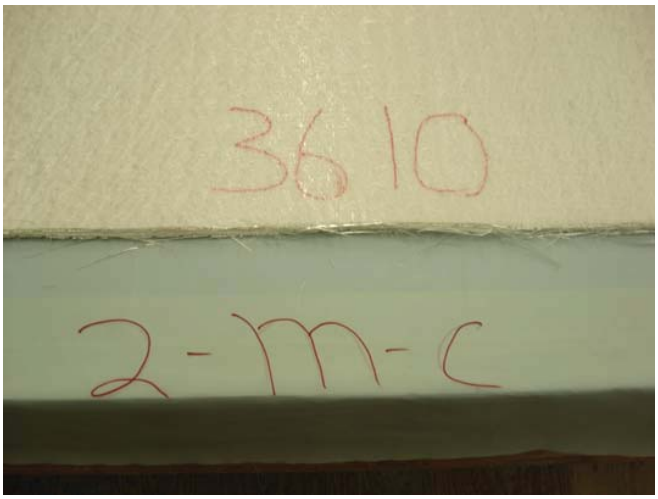
1st Layer – CFM



2nd Layer – E-LT 1603

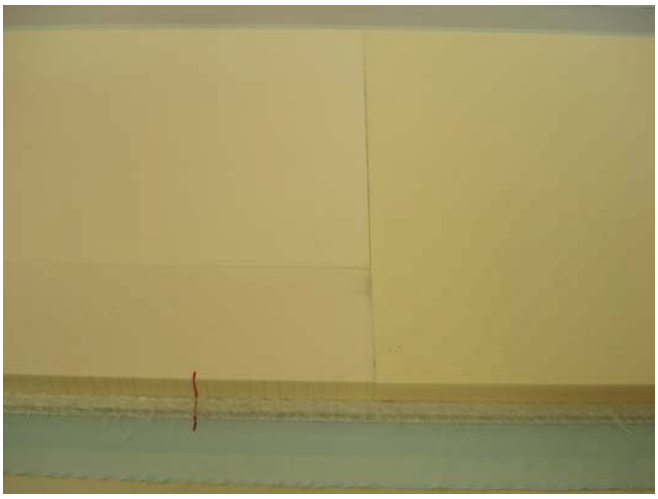


3rd Layer – E-LT 3610

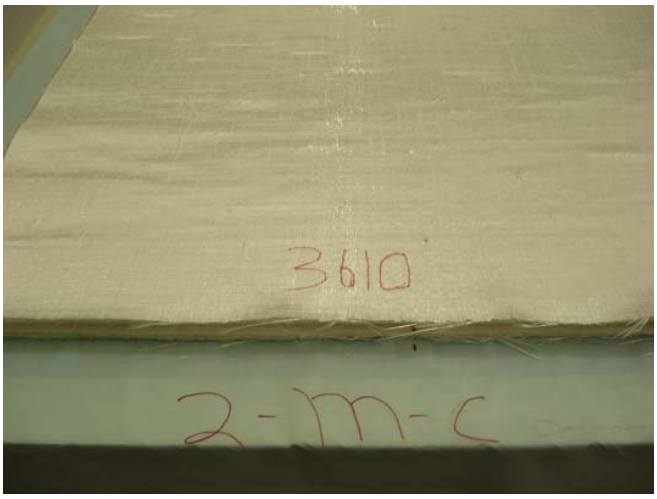


4th Layer – E-LT 3610

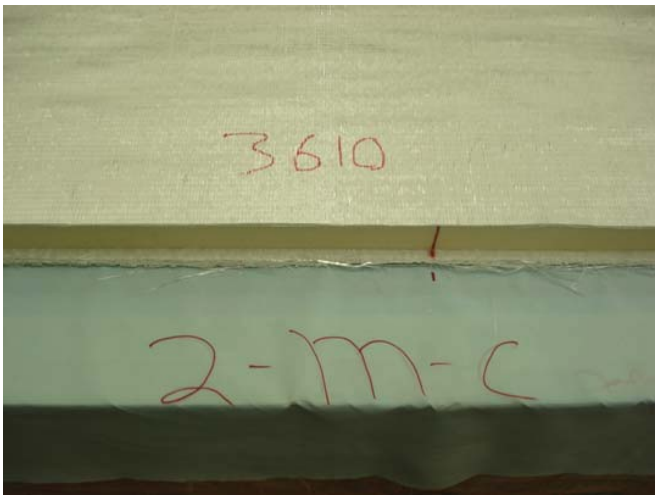
HODGDON SHIPBUILDING



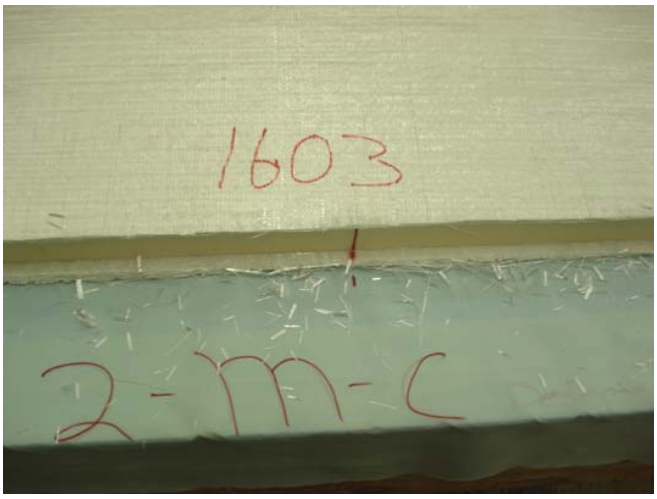
5th Layer – H100 (1.5) Core



6th Layer – E-LT 3610



7th Layer – E-LT 3610



8th Layer – E-LT 1603

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-M-S***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 11/22/2010 **Shop Temperature:** 68 °F

Name(s): Chad Jones **Humidity:** 42 %RH

Start: 7:55 **AM** / PM Vacuum Level: 29 ¼ "of Hg
Stop: 8:10 **AM** / PM Vacuum Level: 28 ¾ "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-M-S***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 11/22/2010 **Shop Temperature:** 68 °F

Name(s): Donald Soohey **Humidity:** 42 %RH

Infusion:

Start: 10:35 **AM** / PM Temp: 71 °F Vacuum Level: 29 ¼ "of Hg

Stop: 10:52 **AM** / PM Temp: 74 °F Vacuum Level: 29 ¼ "of Hg

Comments: Infused in 17 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 2-M-S

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-M-S***

Data Sheet for Infusing Composite Structures

Date: 11/15/2010 **Shop Temperature:** °F

Name(s): Donald Soohey **Humidity:** %RH

LAY-UP EXAMINATION

Panel Lay-Up:

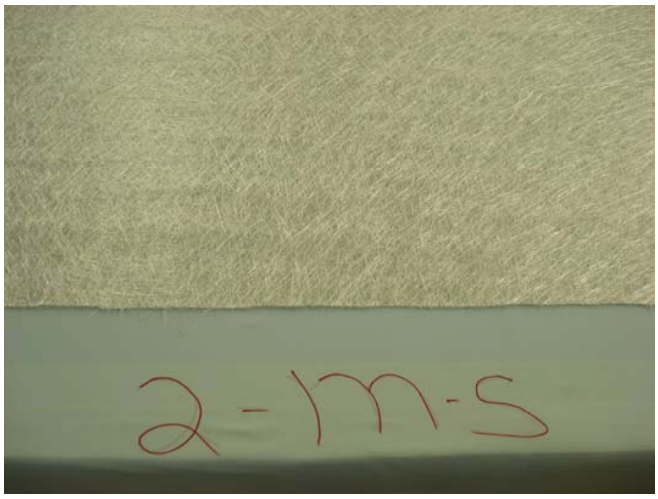
Ply 1 is ply closest to table/mold

Add sheets if necessary

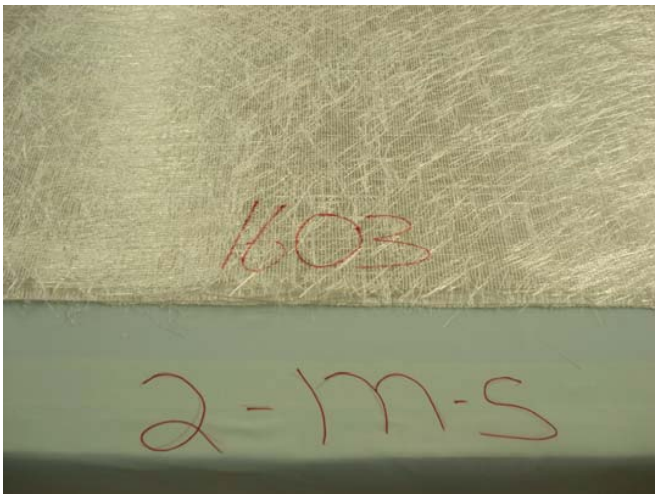
Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		CFM			√
2		E LT 1603			√
3		E LT 3610			√
4		E LT 3610			√
5		H100 (1.5)			√
6		E LT 3610			√
7		E LT 3610			√
8		E LT 1603			√

Core Thickness: 1.5”

HODGDON SHIPBUILDING



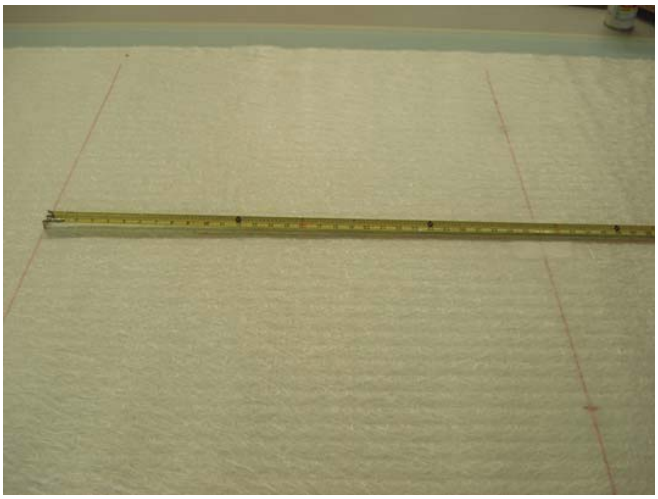
1st Layer – CFM



2nd Layer – E-LT 1603

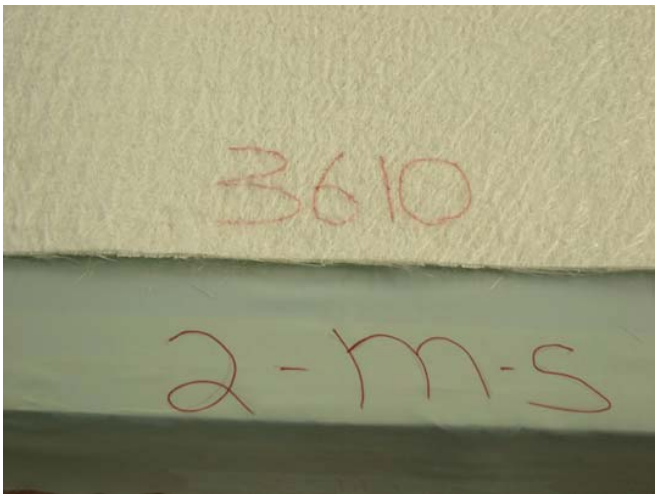


3rd Layer – E-LT 3610



Defects

HODGDON SHIPBUILDING



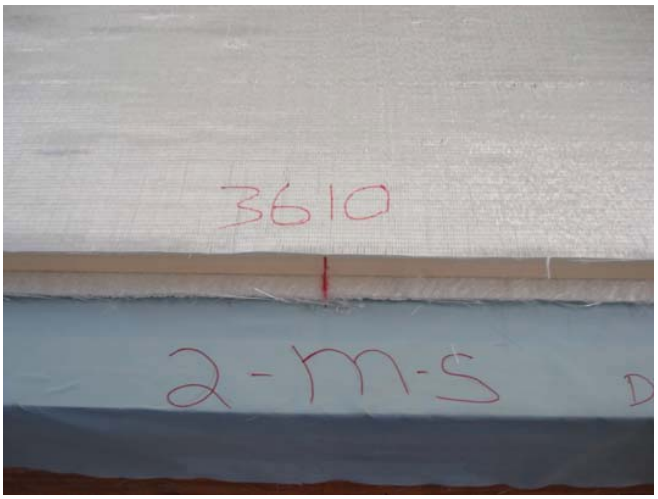
4th Layer – E-LT 3610



5th Layer – CLT 1800



6th Layer – E-LT 3610



7th Layer – E-LT 3610

HODGDON SHIPBUILDING



8th Layer – E-LT 1603

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-M-S***

Data Sheet for Infusing Composite Structures

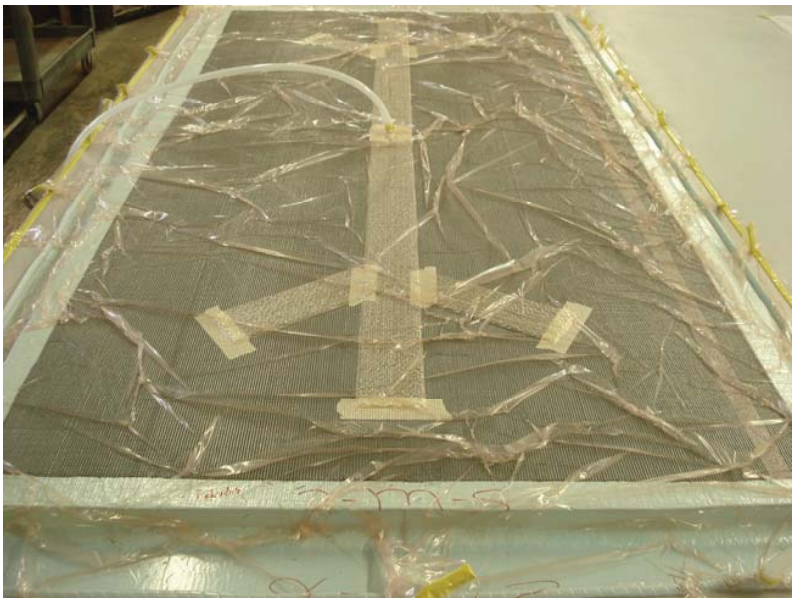
VACUUM INTEGRITY TEST POST LAY-UP

Date: 11/16/2010 **Shop Temperature:** 72.5 °F

Name(s): Chad Jones **Humidity:** 33 %RH

Start: 10:10 **AM** / PM Vacuum Level: 28 "of Hg
Stop: 10:25 **AM** / PM Vacuum Level: 27 ¾ "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***2-M-S***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 11/16/2010 **Shop Temperature:** 72 °F

Name(s): Donald Soohey **Humidity:** 33 %RH

Infusion:

Start: 10:40 **AM** / PM Temp: 73 °F Vacuum Level: 28 "of Hg

Stop: 10:56 **AM** / PM Temp: 79 °F Vacuum Level: 28 "of Hg

Comments: Infused in 16 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 3-M-C

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-M-C***

Data Sheet for Infusing Composite Structures

Date: 11/02/2010 **Shop Temperature:** °F

Name(s): Donald Soohey **Humidity:** %RH

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		KBX 1308			√
3		CBX 1800			√
4		CLA 1812			√
5		CBX 1800			√
6		M100 (1.0)			√
7		CFM			√
8		M100 (1.0)			√
9		CBX 1200			√
10		CLA 1812			√
11		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-M-C***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 11/02/2010 **Shop Temperature:** 73 °F

Name(s): Chad Jones **Humidity:** %RH

Start: 2:25 AM / **PM** Vacuum Level: 25 ½ "of Hg
Stop: 2:40 AM / **PM** Vacuum Level: 25 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***3-M-C***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 11/02/2010 **Shop Temperature:** 73 °F

Name(s): Donald Soohey **Humidity:** %RH

Infusion: Resin Temp: 69 °F

Start: 2:53 AM / **PM** Temp: 73 °F Vacuum Level: 25 "of Hg

Stop: 3:40 AM / **PM** Temp: 81 °F Vacuum Level: 25 "of Hg

Comments: Infused in 47 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 4-M-C

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-M-C***

Data Sheet for Infusing Composite Structures

Date: 11/01/2010 **Shop Temperature:** °F

Name(s): John Levins **Humidity:** %RH

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		CBX 1800			√
3		CLA 1812			√
4		CBX 1200			√
5		M80 (1.0)			√
6		CBX 1200			√
7		CLA 1812			√
8		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-M-C***

Data Sheet for Infusing Composite Structures

VACUUM INTEGRITY TEST POST LAY-UP

Date: 11/02/2010 **Shop Temperature:** 68 °F

Name(s): Chad Jones **Humidity:** %RH

Start: 6:45 **AM** / PM Vacuum Level: 26 "of Hg
Stop: 7:00 **AM** / PM Vacuum Level: 26 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-M-C***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 11/02/2010 **Shop Temperature:** 69 °F

Name(s): John Levins **Humidity:** %RH

Infusion:

Start: 8:05 **AM** / PM Temp: 73 °F Vacuum Level: 26 "of Hg

Stop: 8:55 **AM** / PM Temp: 74.3 °F Vacuum Level: 26 "of Hg

Comments: Infused in 50 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 4-M-S

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-M-S***

Data Sheet for Infusing Composite Structures

Date: 10/11/2010 **Shop Temperature:** 79 °F

Name(s): John Levins **Humidity:** 27 %RH

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold

Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		CBX 1800			√
3		CLA 1812			√
4		CBX 1200			√
5		M80 (1.0)			√
6		CBX 1200			√
7		CLA 1812			√
8		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***4-M-S***

Data Sheet for Infusing Composite Structures

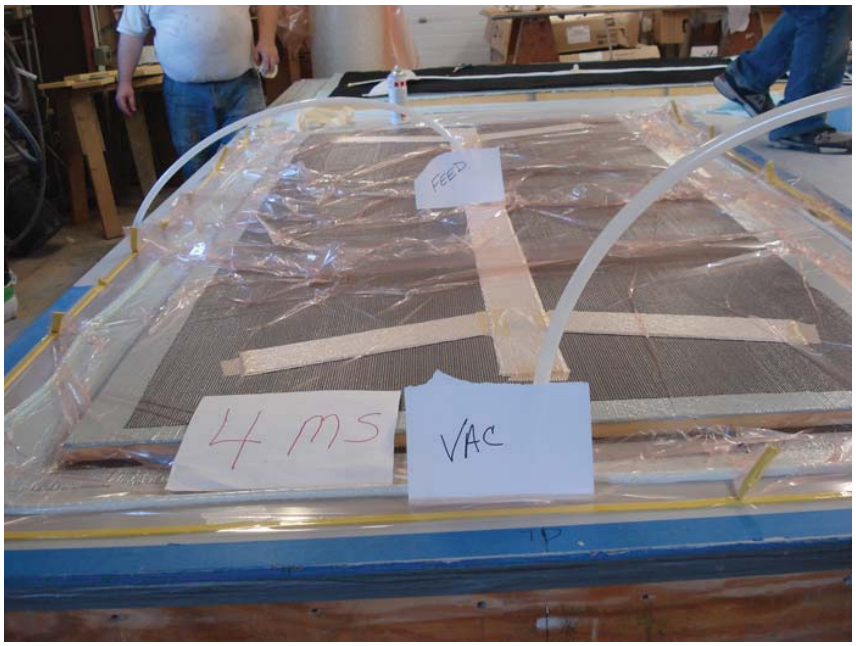
VACUUM INTEGRITY TEST POST LAY-UP

Date: 10/11/2010 **Shop Temperature:** 77 °F

Name(s): John Levins **Humidity:** 27.1 %RH

Start: 3:30 AM / **PM** Vacuum Level: 28 "of Hg
Stop: 3:45 AM / **PM** Vacuum Level: 28 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: 0632

Part Number: 4-M-S

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 10/11/2010 **Shop Temperature:** 75 °F

Name(s): Jason Wight **Humidity:** 27 %RH
Sara Boston

Infusion:

Start:	4:00 AM / **PM**	Temp:	78 °F	Vacuum Level:	28 "of Hg
Stop:	4:25 AM / **PM**	Temp:	°F	Vacuum Level:	28 "of Hg

Comments: Infused in 25 minutes

HODGDON SHIPBUILDING

DATA SHEET FOR INFUSING COMPOSITE STRUCTURES

Project Number: 0632

Part Number: 5-M-S

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-M-S***

Data Sheet for Infusing Composite Structures

Date: 11/08/2010 **Shop Temperature:** 71.3 °F

Name(s): Donald Soohey **Humidity:** %RH
John levins

LAY-UP EXAMINATION

Panel Lay-Up:

Ply 1 is ply closest to table/mold
Add sheets if necessary

Ply #	Orientation	Material	Vendor	Lot/Batch Number	QA Check
1		Veil			√
2		KBX 1308			√
3		KBX 1308			√(-45)
4		KBX 1308			√(+45)
5		ECFM			√
6		M80 (1.5)			√
7		CLT 1800			√
8		CBX 1200			√

Core Thickness: __

HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-M-S***

Data Sheet for Infusing Composite Structures

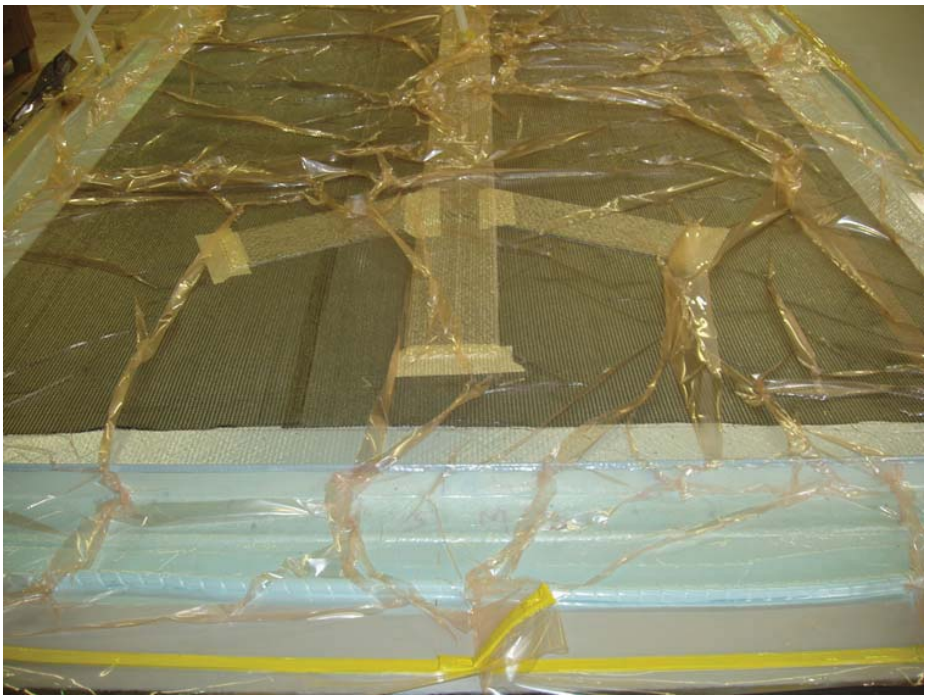
VACUUM INTEGRITY TEST POST LAY-UP

Date: 11/09/2010 **Shop Temperature:** 73 °F

Name(s): Chad Jones **Humidity:** 25 %RH

Start: 10:25 **AM** / PM Vacuum Level: 26.5 "of Hg
Stop: 10:40 **AM** / PM Vacuum Level: 26 "of Hg
(Duration ≥ 15 min) (Leakage ≤ 1" of Hg)

Sketch or Digital Picture of Lay-up with approximate dimensions, exit & feed lines



HODGDON SHIPBUILDING

Project Number: ***0632***

Part Number: ***5-M-S***

Data Sheet for Infusing Composite Structures

INFUSION DATA

Date: 11/09/2010 **Shop Temperature:** 74 °F

Name(s): Donald Soohey **Humidity:** %RH
John Levins

Infusion:

Start: 12:25 AM / **PM** Temp: 74 °F Vacuum Level: 26.5 "of Hg
Stop: 1:05 AM / **PM** Temp: 76 °F Vacuum Level: 26.5 "of Hg

Comments: Infused in 35 minutes

Appendix E
Fatigue Test Report Addendum







Advanced Design and Optimization of High Performance Combatant Craft:

Material Testing and Computational Tools

Task 1 Addendum Report

December 19, 2011

Office of Naval Research
Contract No. N00014-10-C-0037

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Executive Summary

Composite sandwich panels with known defects were constructed within Task 1 of the Office of Naval Research Contract No. N00014-10-C-0037, "Advanced Design and Optimization of High Performance Combat Craft: Material Testing and Computational Tools". A four-point flexural fatigue testing process was developed and executed. The panels were subjected to a 30-year fatigue loading spectrum representing the in-service loads that a vessel experiences. The Test Plan originally anticipated that at least a percentage of the panels would fail near the end of the fatigue testing as a result of defect propagation or stress concentrations around the defects. However, none of the panels failed and no evidence of defect propagation was found using non-destructive testing methods. An investigation of the observed panel behavior was conducted by analyzing the fatigue testing data and reviewing the relevant literature. It was concluded that the lack of damage and panel failure is attributable to using a fatigue spectrum designed for fully reversed bending while implementing one-sided bending during testing. The observed panel behavior agrees with the behavior of composite sandwich panels subjected to fatigue testing reported on by the literature. The stiffness of the panels seems to be constant until a point close to failure, when the panel stiffness begins to decreases. Recommendations for future 30-year fatigue testing are also included.

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1. Introduction

Composite sandwich panels with known defects were constructed within Task 1 of the Office of Naval Research Contract No. N00014-10-C-0037, "Advanced Design and Optimization of High Performance Combat Craft: Material Testing and Computational Tools". A four-point flexural fatigue testing process was developed and executed. In the absence of a load spectrum specific to smaller, high speed craft, the University of Maine - AEWC employed a 30-year fatigue spectrum derived from sag/hog loading histories of large, 90-180m (300-600 ft) vessels developed under the Next Navy Composites (N2C) program.

The Test Plan originally anticipated that at least a percentage of the panels would fail near the end of the fatigue testing as a result of defect propagation or stress concentrations around the defects. However, none of the panels failed and no evidence of defect propagation was found using ultrasonic testing (UT) methods. As a result, additional fatigue testing was conducted. The panels were subjected to 5,000 cycle constant amplitude fatigue blocks starting at an amplitude of 50% of the average ultimate baseline panel load. The amplitude of each subsequent block was increased by 5% of the average baseline panel ultimate load. Static tests to determine panel stiffness and UT inspections around defects were conducted between each fatigue block. Most panels were able to survive fatigue blocks with amplitudes much higher than 50% of ultimate with some panels surviving loads at 90-95% of ultimate.

1.1. Problem Statement

The results of the fatigue testing performed on composite sandwich panels within Task 1 of the project were unexpected. In every panel and defect configuration no damage was found after the application of the 30-year fatigue spectrum. As a result, it was necessary to investigate the development of the fatigue spectrum and the behavior of the composite sandwich panels.

1.2. Project Objectives

The project team sought to identify the factors that contributed to the prolonged and unanticipated panel lifespan. The investigation included:

1. Literature research in order to determine if similar results have been seen by others and if alternative fatigue damage accumulation prediction techniques have been proposed for similar sandwich panel construction.
2. An analysis of the fatigue data in order to characterize the behavior of the panels during testing.

2. Literature Review

2.1. Literature Review Objectives

An extensive literature review was conducted in order to identify relevant publications. A number of publications were subsequently selected for review in order to:

- Better understand the behavior of the composite sandwich panels subjected to fatigue loading,
- Determine if similar results have been seen by others and
- Determine if alternative fatigue damage accumulation prediction techniques have been proposed for similar sandwich panel construction.

2.2. Literature

The following sections present the articles selected for review and include a brief description of each article. The findings and relevant observations from the articles are further discussed in section 4.3 of this report.

2.2.1. Fatigue of Foam Core Sandwich Beams–2: Effects of Initial Damage, International Journal of Fatigue, 1997

Burman and Zenkert [1] conducted both static and constant amplitude fatigue bending tests on composite sandwich beams. The beams included both damaged and undamaged specimens. Of the damaged specimens two defect types were investigated, a flawed butt joint and an interface disbond similar to Task 1 of the project. By testing both damaged and undamaged beams the effects of initial damage were quantified.

2.2.2. Modelling the Fatigue Behaviour of Sandwich Beams Under Monotonic, 2-Step and Block-Loading Regimes, Composites Science and Technology, 1999

Clark et al. [2] examined the effects of block loading sequences on three different composite sandwich panel damage accumulation models. One damage accumulation model was linear whereas the other two were non-linear. The non-linear models more closely reflected the observed behavior of composite sandwich panels subjected to fatigue loading whereas the panel stiffness seemed to decrease the fastest towards the end of the fatigue lifespan.

2.2.3. *Fatigue Charecteristicts,* Composite Materials In Maritime Structures, Volume 2: Practical Considerations, 1993

Scholte [3] provided an overview of the fatigue behavior of composites, including a discussion on the use of the Palmgren-Miner damage accumulation rule. The typical fatigue behavior of composite sandwich panels subjected to fatigue bending was also described.

2.2.4. Modelling the Flexural Behaviour of Sandwich Composite Materials Under Cyclic Fatigue, Materials and Design, 2004

El Mahi et al. [4] investigated the use of an alternative damage accumulation function. Unlike the other models investigated, panel failure was not defined as total failure but as some percentage of stiffness reduction (i.e., a 10% reduction in stiffness) which precedes specimen failure.

2.2.5. Generation and Use of Standardised Load Spectra and Load-Time Histories, International Journal of Fatigue, 2005

Heuler and Klätschke [5] discussed the use and development of standardized load spectra or load histories similar to the 30-year fatigue spectrum developed for Task 1 of the project. A number of standardized load histories in use today in various industries were also summarized.

3. Methodology

3.1. Fatigue Spectrum Analysis

In order to better understand the fatigue behavior of the composite sandwich panels the 30-year fatigue spectrum was analyzed along with the literature on which the development of the fatigue spectrum was based. Further analysis of the fatigue spectrum was conducted by reviewing other relevant literature and analyzing the fatigue spectrum using the data collected during fatigue testing, as described in section 4.1.3 of this report.

3.2. Fatigue Data Analysis

In order to better understand the fatigue behavior of the composite sandwich panels the data generated during additional block fatigue testing was analyzed. Stiffness tests and UT inspections were performed between each constant amplitude fatigue block beyond the application of the 30-year fatigue spectrum. In this manner any degradation in stiffness or propagation of damage that occurred during the application of an additional constant amplitude fatigue block could be observed.

4. Discussion

4.1. Fatigue Spectrum

The fatigue behavior of a specimen is affected by the fatigue spectrum to which it is subjected. In order to understand the fatigue behavior of the composite sandwich panels the development and application of the 30-year fatigue spectrum had to be analyzed. Further analysis of the fatigue spectrum was conducted by analyzing the data which was acquired during fatigue testing.

4.1.1. Fatigue Spectrum Development

The method used to determine a suitable 30-year variable amplitude fatigue spectrum is based on a linear damage accumulation model (the Palmgren-Miner damage rule) and sag/hog loading data for large, 90-180 m (300-600 ft) vessels from the Next Navy Composites (N2C) program [6]. The fatigue spectrum that was developed simulates the distribution of higher-probability, low amplitude cycles with lower-probability, high amplitude cycles.

The 30-year load histogram had to be scaled in order for it to be applicable to the specific materials and panel configurations that were being tested. The steps taken in Blake [7] were to:

1. Determine the slope of the S-N curve (A) for constant amplitude fatigue testing of the same material
2. Determine the theoretical number of cycles to failure (N_i) for each stress index (SI_i)

$$\boldsymbol{N_i = e^{\left(\frac{SI_i - 1}{A}\right)}} \quad \textbf{(1)}$$

3. Adjust the scale factor (SF), so that the sum of the ratio of number of cycles (n_i) to N_i for each SI_i is equal to one. The sum of n_i/N_i for each SI is the total damage (D) and is the application of the Palmgren-Miner damage rule

$$\boldsymbol{D = \sum_{i=1}^{k} \frac{n_i}{e^{\left(\frac{SI_i * SF - 1}{A}\right)}}} \quad \textbf{(2)}$$

The 30-year spectrum was then converted into one 5-year spectrum and twenty-five 1-year spectra by dividing the total number of cycles for each SI by 6 or 30 respectively. For the purposes of testing, the 5-year spectrum followed by twenty five 1-year spectra would constitute the 30-year fatigue spectrum.

4.1.2. Task 1 Fatigue Spectrum Development and Application

When developing the 30-year fatigue spectrum for Task 1 of the project constant amplitude fatigue data for the sandwich panels being tested were not available. As a result, the slope of the S-N curve (the constant A) could not be determined. Without A the SF could not be obtained using the method outlined by Blake. A SF of 0.5 was chosen based on the American Bureau of Shipping (ABS) Guide for Building and Classing Naval Vessels [8]. The ABS Guide recommends assuming a knockdown factor of 0.5 (or 50% of the static panel strength) in the absence of stress strain data for the material that is being tested. The knockdown factor, which is analogous to the SF, was reasonable since the SF in the example material presented in the N2C document [6] was 44% of the ultimate panel strength and the SF for the Blake [7] testing was determined to be 51.5% of the ultimate panel strength. The knockdown factor was then applied directly to the 5 and 1-year load spectra developed by Blake. Although the amplitudes of the fatigue spectrum were scaled in the same manner as in the literature, no accommodations were made for going from fully reversed fatigue testing to the one-sided fatigue testing used for the purposes of this test.

Table 1 is an excerpt from a spreadsheet used to calculate the one and five-year load spectra [9]. An ultimate load of 222 kN (50 kips) has been assumed for this example. The combined spectra are further illustrated in Figure 1, below.

Table 1. Sample one and five-year load spectra

Load Step	1-year Sequence		5-year Sequence	
	Cycles	Amplitude	Cycles	Amplitude
#	*quantity*	*kN (kip)*	*quantity*	*kN (kip)*
1	3044	39.8 (8.95)	15500	39.8 (8.95)
2	1648	43.7 (9.82)	8500	43.7 (9.82)
3	892	47.55 (10.69)	4750	47.55 (10.69)
4	483	51.42 (11.56)	2625	51.42 (11.56)
5	261	55.34 (12.44)	1375	55.34 (12.44)
6	141	59.21 (13.31)	706	59.21 (13.31)
7	76	63.08 (14.18)	382	63.08 (14.18)
8	41	66.95 (15.05)	207	66.95 (15.05)
9	22	70.82 (15.92)	112	70.82 (15.92)
10	12	74.69 (16.79)	60	74.69 (16.79)
11	7	78.56 (17.66)	33	78.56 (17.66)
12	4	82.47 (18.54)	18	82.47 (18.54)
13	2	86.34 (19.41)	10	86.34 (19.41)
14	1	90.21 (20.28)	5	90.21 (20.28)
15	1	94.08 (21.15)	3	94.08 (21.15)
16	1	97.95 (22.02)	2	97.95 (22.02)
17	1	94.08 (21.15)	1	101.8 (22.89)
18	1	90.21 (20.28)	1	111.2 (25.00)
19	2	86.34 (19.41)	1	101.8 (22.89)
20	4	82.47 (18.54)	2	97.95 (22.02)
21	7	78.56 (17.66)	3	94.08 (21.15)
22	12	74.69 (16.79)	5	90.21 (20.28)
23	22	70.82 (15.92)	10	86.34 (19.41)
24	41	66.95 (15.05)	18	82.47 (18.54)
25	76	63.08 (14.18)	33	78.56 (17.66)
26	141	59.21 (13.31)	60	74.69 (16.79)
27	261	55.34 (12.44)	112	70.82 (15.92)
28	483	51.42 (11.56)	207	66.95 (15.05)
29	892	47.55 (10.69)	382	63.08 (14.18)
30	1648	43.7 (9.82)	706	59.21 (13.31)
31	3044	39.8 (8.95)	1375	55.34 (12.44)
32			2625	51.42 (11.56)
33			4750	47.55 (10.69)
34			8500	43.7 (9.82)
35			15500	39.8 (8.95)

Fatigue loads were applied by running the five-year spectrum as a break-in period followed by twenty five 1-year spectra. As a result, 400,354 cycles are in each 30-year fatigue spectrum. The 30-year fatigue spectrum was applied to all of the composite sandwich panels. At the completion of the 30-year fatigue spectrum testing, none of the panels failed or exhibited evidence of defect propagation using UT inspection techniques. As a result, additional constant amplitude fatigue blocks were applied to the panels in order to either fail the panels or initiate defect propagation.

Each additional fatigue block consisted of 5,000 constant amplitude fatigue cycles. The amplitude of the first block was equal to 50% of the average ultimate static strength of the undamaged baseline panels and increased for each subsequent block by 5% of ultimate strength until panel failure [9]. The 30-year fatigue spectrum and additional fatigue blocks are illustrated in Figure 1. Stiffness tests and UT inspections were performed on each panel between each additional fatigue block. The maximum load of each stiffness test was equal to the amplitude of the previous fatigue block. Figure 1 represents the fatigue loading on a panel that failed during application of the 80% of ultimate strength fatigue block. Some panels failed during lower amplitude fatigue blocks while other panels failed after the application of additional fatigue blocks at higher amplitudes.

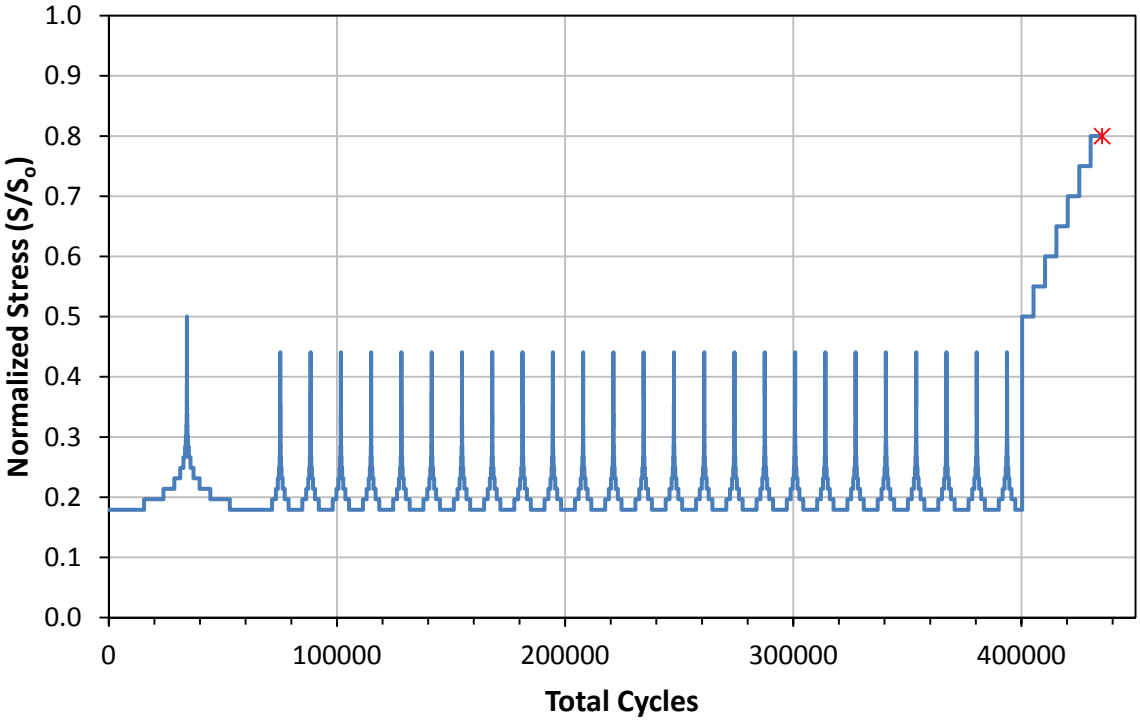


Figure 1. Fatigue spectrum with additional fatigue blocks

4.1.3. Fatigue Spectrum Post Testing Analysis

The additional fatigue blocks were subsequently included in the damage accumulation model in order to estimate an experimental value for A, the slope of the S-N diagram for the material and panel configuration that was being tested. The summation of D was set to include the additional fatigue blocks and the experimental value for A, or A', was adjusted until D was equal to one (equations 1 and 2) as is shown in Table 2a, below. Using A' and not including the additional blocks of cycles, a new SF, or SF', was calculated using the method outlined by Blake [7] but based on the actual testing that was conducted (Table 2b). SF' was found to range from 0.75 to 0.99 for the various panel configurations. Table 2 (a) and (b) are based on the 5_M_S panel. Although SF' may be reasonable for the one-sided fatigue testing that was implemented, it is not a practical design value for hull panels experiencing fully reversed bending throughout their in-service lifespan. A SF of 0.5 may have been appropriate for fully reversed fatigue testing but was too low for the one-sided fatigue testing that was implemented. The low SF is a likely cause of the lack of panel failure and damage propagation that was observed.

Table 2. Damage accumulation model used to find A'(a) and SF' based on A' (b)

(a)				(b)	
SI	n_i	N_i	n_i/N_i	N_i	n_i/N_i
0.358	775000	7491510542358	0.0000	15200638519	0.0001
0.393	425000	3991587064489	0.0000	4427368863	0.0001
0.428	237500	2126776329461	0.0000	1289524452	0.0002
0.463	131250	1134113142397	0.0000	376197214	0.0003
0.497	68750	604272172250	0.0000	109571965	0.0006
0.532	35300	322230881847	0.0000	31965790	0.0011
0.567	19100	171689355903	0.0000	9310421	0.0021
0.602	10350	91478615462	0.0000	2711772	0.0038
0.637	5600	48781387401	0.0000	791114	0.0071
0.672	3000	25991441090	0.0000	230422	0.0130
0.707	1650	13860054074	0.0000	67222	0.0245
0.741	900	7384840780	0.0000	19579	0.0460
0.776	500	3934751845	0.0000	5703	0.0877
0.811	250	2098224302	0.0000	1664	0.1503
0.846	150	1117964786	0.0000	485	0.3096
0.881	50	596159803	0.0000	141	0.3537
0.916	0	317642716	0.0000	41	0.0000
1.000	0	69306909	0.0000	2	0.0000
Additional Blocks				D=	1.0
0.50	5000	69306909	0.0001	SF'=	0.98
0.55	5000	11394595	0.0004		
0.60	5000	1873360	0.0027		
0.65	5000	307995	0.0162		
0.70	5000	50637	0.0987		
0.75	5000	8325	0.6006		
0.80	385	1369	0.2813		
0.85	0	225	0.0000		
0.90	0	37	0.0000		
0.95	0	6	0.0000		
		D=	1.0		
		A' =	-0.0277		

4.2. Data Analysis

Actuator load cell and cross-head displacement measurements were taken during the quasi-static tests conducted on the undamaged baseline panels and between each additional fatigue block on the damaged panels after the application of the 30-year fatigue spectrum. Data was not collected prior to the application of the additional fatigue blocks on the damaged panels subjected to fatigue loading. The stiffness of the panels was computed as the ratio between the load and the actuator displacement.

Table 3, below, presents the stiffness of the undamaged baseline panels and the ultimate panel strength. The baseline panel labeling notation uses the panel type (1 thru 5) followed by a 'b' (baseline) and finally the panel number (first or second panel tested).

Table 3. Undamaged baseline panel stiffness and ultimate quasi-static strength

Panel	Stiffness (lbs/in)	Ult. Strength (lbs)
1b-1	11808	31672
1b-2	11582	30635
2b-1	2761	11859
2b-2	2844	12467
3b-1	4793	10385
3b-2	4699	9545
4b-1	1213	3480
4b-2	1209	3512
5b-1	2014	4558
5b-2	1980	5059

Appendix A, below, presents the stiffness of the damaged panels between each additional fatigue block. Failure occurred for each panel in the block after the last stiffness measurement. The number in parentheses after the final stiffness measurement is the number of cycles that were performed within the final 5,000 cycle constant amplitude fatigue block before failure. For example, in panel 1-B-C failure occurred 4,757 cycles into the constant amplitude fatigue block in which the amplitude was 65% of the average ultimate static strength of the undamaged baseline panels.

Table 4. Panel stiffness (lbs/in) after the application of additional fatigue blocks

Panel	Amplitude of Additional Fatigue Blocks (% of Baseline Panel Ultimate Strength)									
	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
1-B-C	12484	12286	12039	**(4757)**	--	--	--	--	--	--
1-B-S	12304	*	11710	11687	11401	11062	**(1203)**	--	--	--
1-M-S	12487	12271	12091	11868	11680	11417	**(3147)**	--	--	--
2-B-C	2853	2691	**(9)**	--	--	--	--	--	--	--
2-B-S	2839	2797	2758	2712	2667	2619	2551	**(75)**	--	--
2-M-C	2975	2951	2924	**(2749)**	--	--	--	--	--	--
3-B-C	5053	4982	4951	4948	4893	4836	**(19)**	--	--	--
3-B-S	5024	5012	**(3691)**	--	--	--	--	--	--	--
3-M-S	5038	5036	5050	5043	5049	5015	4958	4923	**(18)**	--
4-B-S	1313	1307	1309	1306	1302	1298	1296	**(1884)**	--	--
4-M-C	1328	1331	1318	1306	1308	1304	1294	**(573)**	--	--
4-M-S	1356	1352	1361	1343	1348	1346	1346	1336	1337	**(672)**
5-B-S	2226	2224	2219	2214	2210	2200	2188	**(540)**	--	--
5-M-C	2139	2131	2131	2128	2123	**(1614)**	--	--	--	--
5-M-S	2144	2096	2126	2134	2122	2117	**(385)**	--	--	--

* No data available

The labeling notation uses the panel type (1 thru 5), whether the defect is located on the infusion bag side (B) or mold side (M) of the composite sandwich panel and whether the defect was located within the composite skin plies (S) or at the composite skin and foam core interface (C). For example, the panel 1-B-C is panel type 1 with the defects located on the infusion bag side of the composite sandwich panel between the composite skin and foam core. The defects consisted of 25.4, 50.8, and 101.6 mm (1, 2, and 4 in.) squares of plastic laminate sheeting inserted either between the composite skin plies or at the composite skin and foam core interface. The defects created delaminations in the composite sandwich panel which were meant to simulate actual defects which may occur in the manufacturing process or as a result of damage [9].

The relatively low spread in the panel stiffness measurements after the application of the 30-year fatigue spectrum (0-5%) indicates that the location of the panel defects does not have a significant impact on the panel stiffness or the fatigue behavior of the panels. In the absence of stiffness data on the damaged test specimens prior to the 30-year fatigue spectrum it is not possible to directly observe any degradation in stiffness which may have occurred during the application of the 30-year fatigue spectrum. Although the stiffness of the panels after the application of the 30-year fatigue spectrum is within the same range as the undamaged baseline panel stiffness, the spread in stiffness measurements are relatively large (6-11%) and the stiffness of the baseline panels are lower than the stiffness of the damaged panels subjected to the 30-year fatigue spectrum in every case. This discrepancy in stiffness measurements is attributable to testing, material and geometric variability.

For the purposes of analysis the measured stiffness between each additional fatigue block was normalized to the 50% stiffness test for each panel. In this manner any decrease in stiffness which occurred during the additional fatigue blocks could be observed. Figure 2 presents the normalized stiffness measurements for Panel 5. Normalized stiffness plots for all panels are available in Appendix A of this addendum.

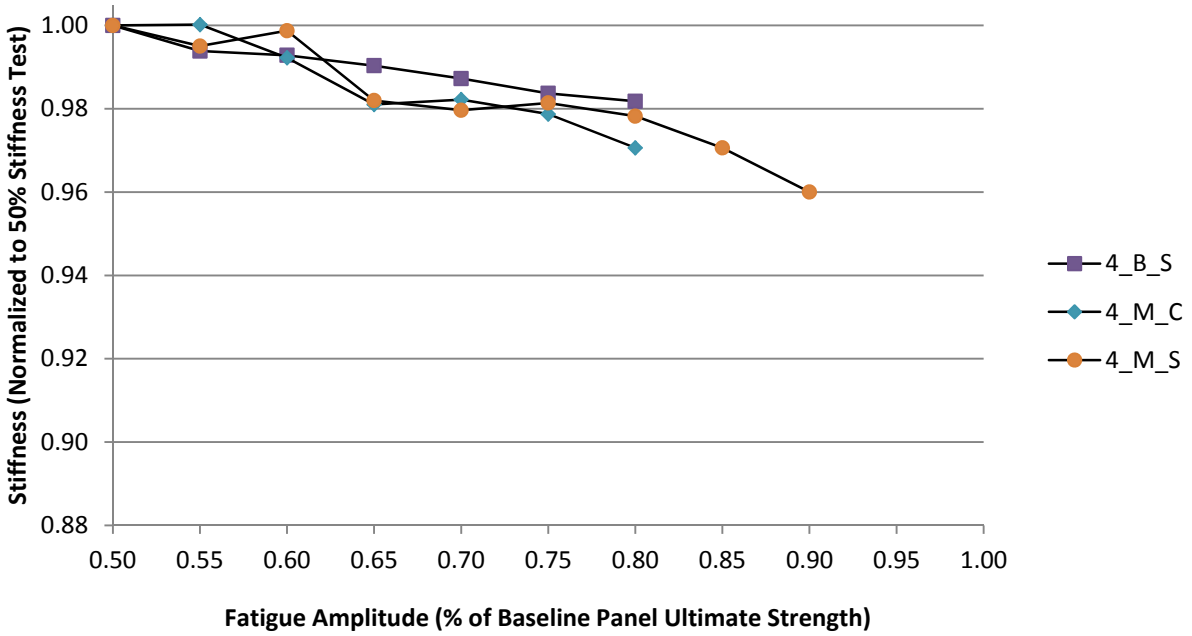


Figure 2. Panel 4 Normalized Stiffness

A decrease in stiffness was generally observed between each additional fatigue block. Panels 3 thru 5 experienced a decrease in stiffness from 2-4%, while panels 1 and 2 experienced a decrease in stiffness from 2-10%. The additional blocks of fatigue cycles represent from 1-11% of the total number of cycles performed for each test, depending on when failure occurred.

The UT inspections which were performed between each additional fatigue block did not give any indication of defect propagation prior to failure.

4.3. Findings from the Literature

The findings from the literature were compared to the observed behavior of the composite sandwich panels, the 30-year fatigue spectrum and the damage accumulation model used to develop the 30-year fatigue spectrum.

4.3.1. Panel behavior

Burman and Zenkert [1] did not observe any degradation in stiffness until after 90-95% of the fatigue cycles were complete. After the initial change in stiffness the decrease in stiffness was rapid. The additional fatigue blocks executed in Task 1 of the project were all within the final 1-11% of the total number of fatigue cycles, depending on when failure occurred. Although stiffness measurements were not taken prior to the application of the 30-year fatigue spectrum, the decrease in stiffness which occurred during the additional fatigue blocks appears to be minimal (2-10%) and coincides with the decrease in stiffness which is expected at the end of the fatigue lifespan. Other authors have also confirmed the behavior which was observed during panel testing. Typically there is no degradation in the stiffness of the panel until after a point of initial fatigue damage. After the initiation of fatigue damage the decrease in stiffness is rapid and precedes failure of the specimen [2], [3]. The manufactured delaminations which seem to have had a minimal contribution to the initiation of fatigue damage because after the application of the 30-year fatigue

spectrum the spread of the stiffness data remained low for like panel types with defects at different locations.

4.3.2. Fatigue spectrum

The use of a standard fatigue spectrum, or standardized load history such as the 30-year fatigue spectrum, is necessary to demonstrate the in-service integrity of the material or structure which is being tested [5]. Some of the other relevant benefits of conducting a standardized load history testing regime include:

- Comparison of the in-service behavior of different materials or structural configurations
- Determination of the allowable design stress levels
- Verification of fatigue life models

It was also noted in Heuler and Klätschke's [5] article that different parts on the same assembly may require different spectra. The 30-year fatigue spectrum which was used for Task 1 of the project was based on the sag/hog loading histories of large, 90-180m (300-600 ft) vessels. Although a hull panel may experience torsion, shear or other in-plane forces along with flexure, the 30-year fatigue spectrum provides a good representation of the global bending which a ship will be subjected to.

During Burman and Zenkert's [1] testing the fatigue threshold for the composite sandwich beams was found to range from 20-40% of the static ultimate load, depending on the core material and stress ratio which was being tested. For comparison purposes, the average stress amplitude ($S_{Average}$) for Task 1 of the project was found for the 30-year fatigue spectrum based on the stress index (SI) and the number of cycles performed at that stress amplitude (n_i).

$$\boldsymbol{S_{Average}} = \frac{\sum_{i=1}^{k} \boldsymbol{SI} * \boldsymbol{n_i}}{\sum_{i=1}^{k} \boldsymbol{n_i}} \quad \textbf{(3)}$$

This weighted average stress intensity was found to be 20% of the static ultimate load of the undamaged baseline panels, potentially below the fatigue threshold for the specimens which were being tested. The relatively low $S_{Average}$ may have contributed to the lack of defect propagation and panel failure that was observed.

Burman and Zenkert [1] performed both fully reversed and one-sided fatigue testing on damaged and undamaged composite sandwich beams. The resulting S-N curves allowed for the direct comparison of the two loading ratios. It was observed that one-sided fatigue loading can take many more cycles to fail the same composite sandwich beam than fully reversed fatigue loading at the same maximum amplitude. The difference in the number of cycles to failure is the greatest at low stress levels and can sometimes exceed 100 times the number of cycles to fail a panel using one sided fatigue bending instead of fully reversed bending. The increase in the number of cycles to failure for one-sided bending versus fully reversed bending is another plausible explanation for why there was no panel failure, or observed defect propagation during the application of the 30-year fatigue spectrum. The 30-year fatigue spectrum originally outlined by Blake [7] was based on fully reversed bending and no accommodations were made for the transition from fully reversed to one-sided bending during Task 1 of the project.

4.3.3. Damage accumulation model

The derivation of the 30-year fatigue spectrum was originally based on a linear damage accumulation model, the Palmgren-Miner damage rule. S-N data was not available for the material and panel configurations which were being tested for Task 1 of the project. Because an assumed slope of the S-N curve was used, the testing which was conducted cannot validate or invalidate the

damage accumulation model. However, further investigation into others use of damage accumulation models with composite sandwich panels was warranted.

According to the literature, composite sandwich panels subjected to fatigue loading typically maintain their stiffness until some point prior to failure when stiffness decreases rapidly [1]-[3]. Similar behavior was observed in the specimens tested during Task 1 of the project. The damage accumulation model that was used to predict the lifespan of the sandwich panels assumed that damage started at zero with the application of the first cycle and then accumulated in a linear manner until failure, when damage was equal to one. This model, however, does not reflect the observed behavior of the panels subject to fatigue loading whereas there does not seem to be any physical accumulation of damage (or loss of stiffness) until after an initial decrease in stiffness. In Clark et al. [2] the number of cycles to the initial decrease in stiffness, or initiation of fatigue damage, at a given stress amplitude is defined as n_{if}. Damage was said to be equal to zero until the point n_{if} was reached. After the number of cycles exceeded n_{if}, damage began to accumulate in either a linear or non-linear manner, depending on the model which was being used. In other words:

$$D(n) = 0 \qquad \text{when } n < n_{if}$$

$$0 < D(n) < 1 \qquad \text{when } n > n_{if} \qquad \textbf{(4)}$$

The point, n_{if}, can be determined by conducting constant amplitude fatigue testing while monitoring stiffness.

One of the three damage accumulation models reported on by Clark et al. [2] was a variation on the linear Palmgren Miner damage rule which incorporated n_{if}, while the other two were non-linear models. One of the two non-linear models was based on the change in shear modulus and the other was based on the change in shear strain over the course of constant amplitude fatigue testing. These models more closely reflect the observed behavior of composite sandwich panels subjected to fatigue loading whereas stiffness seems to decrease the fastest towards the end of the fatigue life of a specimen.

5. Conclusions and Recommendations

5.1. Summary of Findings

The observed behavior of the test specimens was consistent with the relevant literature. During the application of the additional fatigue blocks there was a decrease in stiffness from 2-10% of the stiffness measured after the application of the 30-year fatigue spectrum. The additional fatigue blocks applied after the completion of the 30-year spectrum constituted up to 12% of the total number of cycles to failure and a decrease was stiffness is expected during this portion of the fatigue life.

The lack of panel failure can be attributed to scaling the 30-year fatigue spectrum loads based on an assumed scale factor. A scale factor of 0.5, or 50% of the ultimate load, was chosen based on the ABS Design Guide in the absence of S-N data for the material and panel configurations that were being tested. A scale factor of 0.5 may have been appropriate for fully reversed bending but was too low for the one-sided bending that was implemented. Furthermore, one-sided fatigue bending can cause damage to accumulate at a much slower rate than fully reversed bending. In some cases it can take over 100 times more cycles to fail a composite sandwich panel using one-sided bending than it will to fail the same panel using fully reversed bending at the same maximum or minimum stress. The panels were not subjected to a fatigue test that is representative of the actual in-service loads that a hull panel experiences, whereas only one-sided bending was implemented.

5.2. Recommendations

In order to scale the fatigue life of a composite sandwich panel to survive a 30-year fatigue spectrum, S-N curves for the particular sandwich panel configuration being tested must first be developed. If the linear Palmgren-Miner's rule is to be implemented, then only the number of cycles to failure (N_f) at each stress level needs to be obtained. If one of the non-linear damage accumulation models is to be implemented, then the S-N curves must contain the locations of both N_f and the number of cycles to the initiation of fatigue damage (n_{if}). In order to determine the location of n_{if} the stiffness of the panel subjected to constant amplitude fatigue testing must be monitored.

However, instead of scaling the amplitude of the 30-year fatigue spectrum in order to theoretically fail the specimen after 30 years, a standard 30-year fatigue spectrum is proposed. The amplitude of the testing would be scaled to a standard percentage of the ultimate load and a standard stress ratio would be chosen. Subjecting a specimen to a standard 30-year fatigue spectrum would allow for a more direct comparison of fatigue performance between different panel configurations. Furthermore, the application of a standard spectrum would not require S-N curves for the panel configuration that was tested. Although Task 1 of the project essentially used a standard fatigue spectrum, the spectrum was not representative of the conditions which an actual hull panel experiences since only one-sided bending was implemented.

For example, a specimen would first be subjected to a quasi-static test in order to determine the ultimate load. The 30-year fatigue spectrum would then be scaled using a standard scale factor, or percentage of the ultimate load, and a standard stress ratio would be chosen (e.g., 60% of the ultimate load and fully reversed bending). At the end of the 30-year fatigue spectrum another quasi-static test to failure or a stiffness check would be performed in order to determine the residual strength or decrease in stiffness of the specimen. If the specimen does not fail during the application of the 30-year fatigue spectrum but exhibits a decrease in strength or stiffness then it can be concluded that the fatigue testing has reached a point beyond n_{if}. If there isn't a decrease in static strength or stiffness after the application of the 30-year fatigue spectrum, further testing can be conducted using an increased scale factor or percentage of the ultimate load. A standard 30-year

fatigue spectrum would quickly validate whether or not the scale factor could serve as an appropriate fatigue knockdown factor for a particular panel configuration during the design of a hull.

Using a standard fatigue spectrum and a consistent scale factor allows for a more direct comparison between different composite sandwich panel configurations. Furthermore, by using a standard fatigue spectrum in conjunction with data obtained from S-N curves, different damage accumulation models could be assessed by comparing the theoretical behavior of the composite sandwich panels to the actual behavior during the application of the fatigue spectrum.

Regular stiffness checks are recommended during the application of the 30-year fatigue spectrum. Stiffness checks should be performed before the application of the 30-year spectrum, after the first five years of fatigue and after each subsequent year. Information on the stiffness of the panels while they are subjected to the 30-year fatigue spectrum could prove to be invaluable when investigating the behavior of the specimens. Intermediate stiffness checks would be of particular value if the panel fails before the completion of the 30-year fatigue spectrum or if the specimen is subjected to a standard 30-year fatigue spectrum without having first developed S-N curves.

Fatigue tests on baseline panels without defects are recommended. In the event that a panel fails before the completion of the 30-year fatigue spectrum it would be difficult to conclude what effect, if any, a manufactured defect has on the fatigue behavior of the specimen.

5.3. Future Research

The damage accumulation model which was used by Blake [7] and the models which were proposed by Clark et al. [2] need to be analyzed further for use in real-world applications with composite sandwich panels. Although the models in Clark et al. have been shown to predict the failure of composite sandwich panels subjected to fatigue spectra with a small number of steps or blocks, the models have not been validated for spectra such as the highly variable 30-year fatigue spectrum which was discussed in this report. The 30-year fatigue spectrum represents the actual fatigue loading that may be experienced by a composite sandwich panel as part of a hull assembly and it is critical to determine when failure is likely to occur.

The damage accumulation models for composite sandwich panels could be analyzed by comparing the actual behavior of the panels, for which S-N curves are available, to the behavior predicted by the models over the course of the 30-year fatigue spectrum. In this manner the accuracy of the models could be assessed.

References

[1] M. Burman and D. Zenkert, "Fatigue of foam core sandwich beams-2: effect of initial damage," *International Journal of Fatigue,* vol. 19, no. 7., pp. 563-578, August 1997.

[2] S. D. Clark, R. A. Shenoi, and H. G. Allen, "Modelling the fatigue behaviour of sandwich beams under monotonic, 2-step and block-loading regimes," *Composites Science and Technology,* vol. 59, no. 4, pp. 471-486, March 1999.

[3] H.G. Scholte, "Fatigue Charecteristics," *Composite Materials in Maritime Structure, Volume 2: Practical Considerations*, R. A. Shenoi and J. F. Wellicome, Ed. Cambridge, UK: Cambridge University Press, pp. 178-198, 1993.

[4] A. El Mahi, M. K. Farooq, S. Sahraoui, and A. Bezazi, "Modelling the flexural behaviour of sandwich composite materials under cyclic fatigue," *Materials & Design,* vol. 25, no. 3, pp. 199-208, May 2004.

[5] P. Heuler and H. Klatschke, "Generation and use of standardised load spectra and load-time histories," *International Journal of Fatigue,* vol. 27, no. 8, pp. 974-990, August 2005.

[6] J. R. Speckart, private communication, "Five and One Year Load Spectra for Composite Fatigue Studies," 2007.

[7] S. Blake, "Crack Propagation In Secondary Bonded FRP Composite Joints," M.S. thesis, Civil Engineering, University of Maine, Orono, ME, 2008.

[8] *Guide for Building and Classing Naval Vessels,* American Bureau of Shipping, New York, NY, part 1, ch. 4, section 2, pp. 6-7, 2004.

[9] J. Marquis, "Advanced design and optimization of high performance combat craft: material testing and computational tools". AEWC, Orono, ME, Contract No. N00014-10-C-0037, December 19, 2011.

Appendix A: Normalized Stiffness Plots

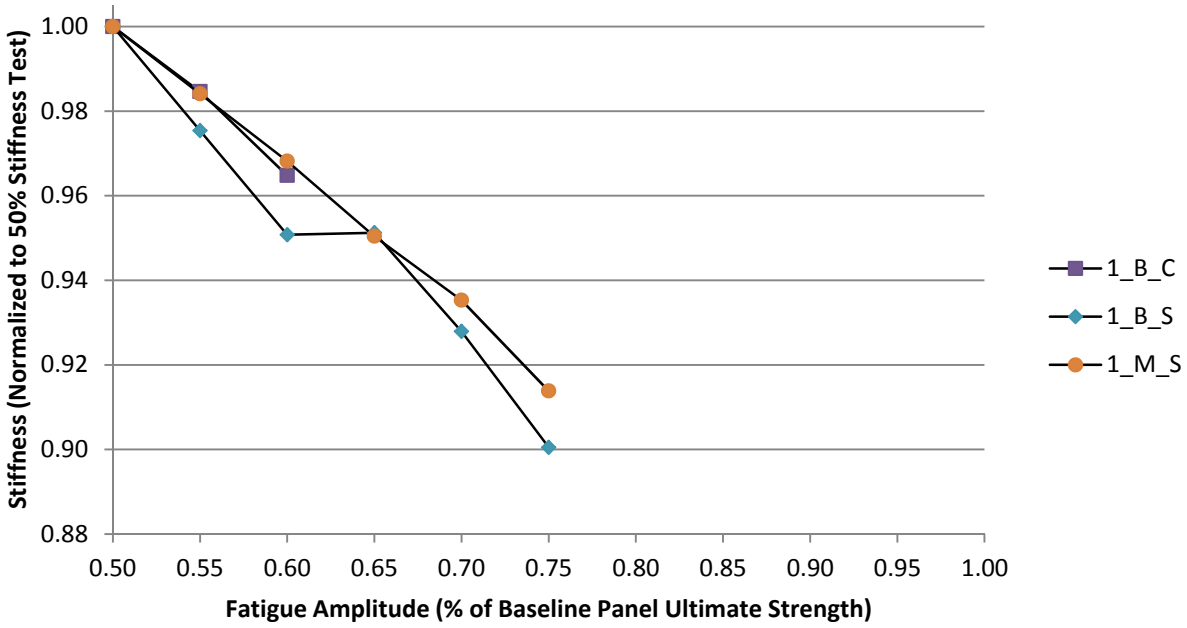


Figure A1. Panel 1 Normalized Stiffness

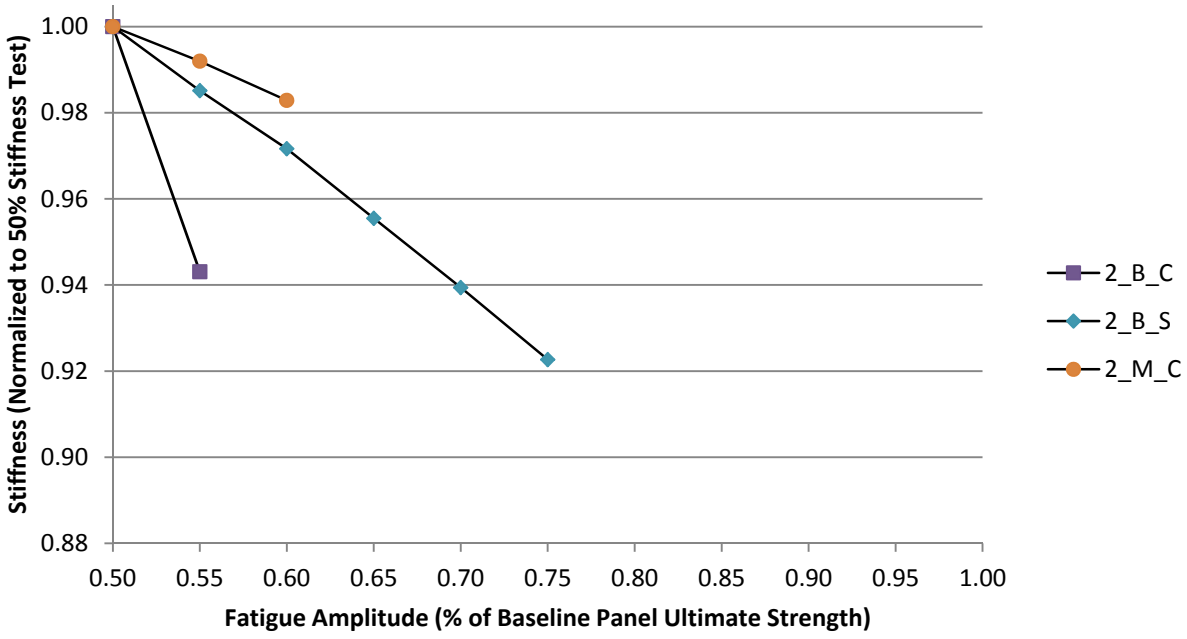


Figure A2. Panel 2 Normalized Stiffness

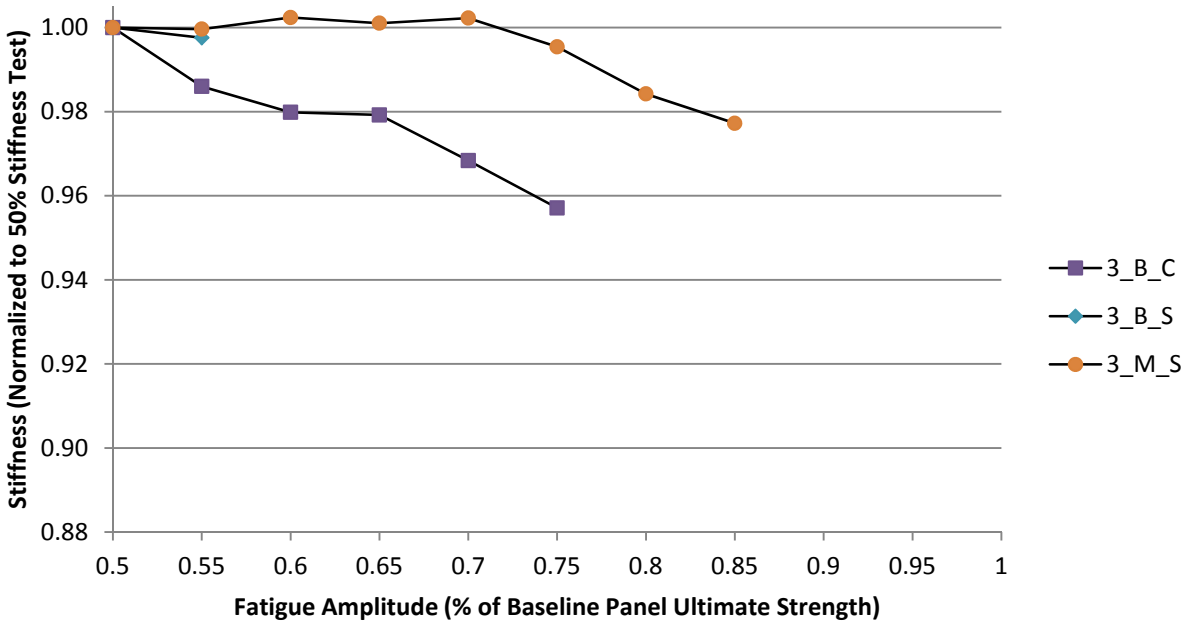


Figure A3. Panel 3 Normalized Stiffness

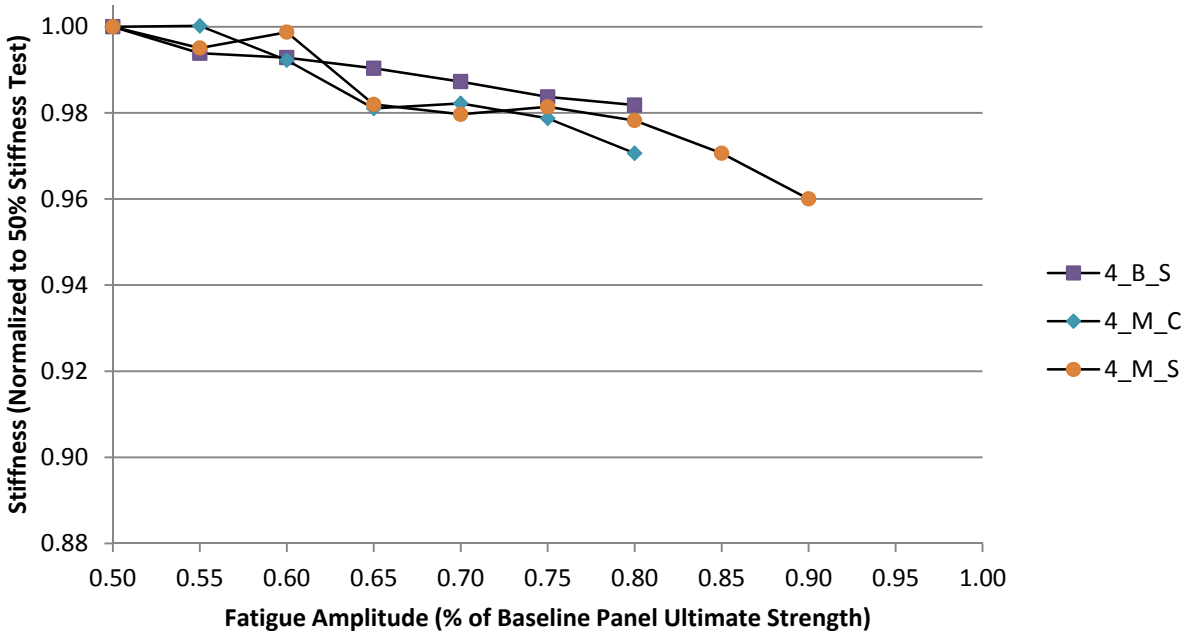


Figure A4. Panel 4 Normalized Stiffness

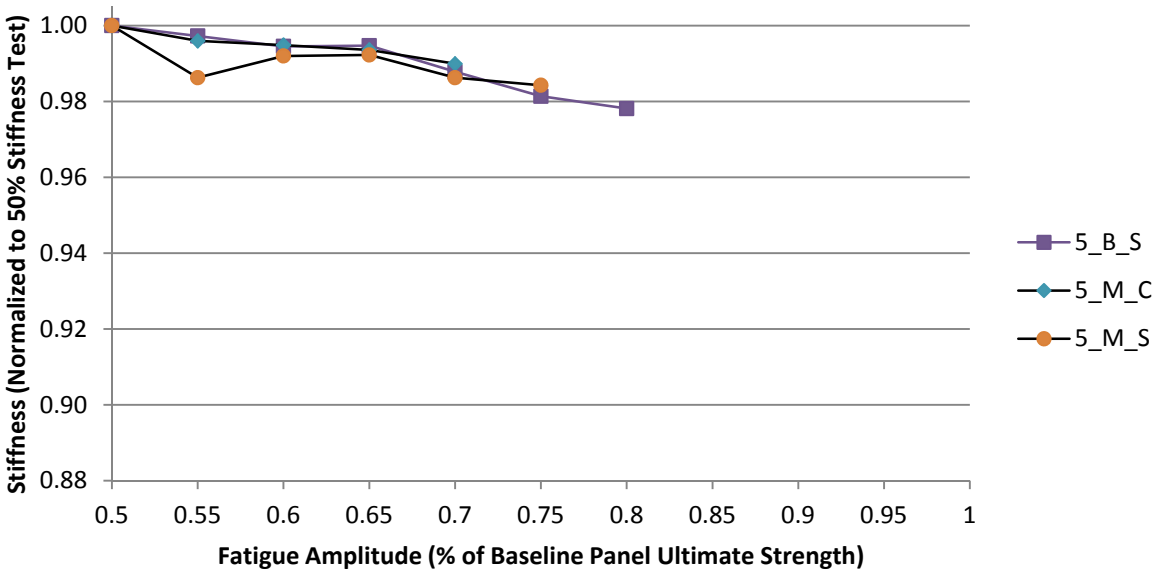


Figure A5. Panel 5 Normalized Stiffness

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Appendix F
Material Property Tests for Modeling

Table F1. Material Property Test Results for Finite Element Modeling (English Units)

Material Property			E-glass		Carbon			Property Obtained From
			E-LTM 1603	E-LTCFM 3610	C-BX 1200	C-BX 1800	C-LA 1812	
			Biaxial (0/90)	*Biaxial (0/90)*	*Double Bias (±45)*	*Double Bias (±45)*	*Unidirectional (0)*	
			Mean (COV)	*Mean (COV)*	*Mean (COV)*	*Mean (COV)*	*Mean (COV)*	
Modulus in the 1, 2, 3 Directions	E_{1t}	*Msi*	3.492 (4.2%)	2.729 (7.8%)	9.016 (1.3%)	9.844 (1.2%)	12.94 (3.5%)	Tension in the 1-dir
	E_{1c}	*Msi*	3.595 (12.8%)	2.689 (11.0%)	8.068 (4.8%)	8.672 (7.5%)	11.63 (5.1%)	Compression in the 1-dir
	E_{2t}	*Msi*	3.309 (5.3%)	*Properties not generated due to balanced lamina*			0.9990 (3.76)	Tension in the 2-dir
	E_{2c}	*Msi*	3.539 (11.6%)				1.060 (8.4%)	Compression in the 2-dir
	E_{3t} [a]	*Msi*	1.682	1.368	1.426	1.554	1.142	Compression in the 3-dir
	E_{3c}	*Msi*	1.682 (5.2%)	1.368 (6.7%)	1.426 (3.6%)	1.554 (8.3%)	1.142 (9.2%)	Compression in the 3-dir
Shear Modulus	G_{12}	*Msi*	0.5983 (11.8%)	0.3868 (14.1%)	0.4611 (4.4%)	0.5207 (9.5%)	0.5793 (16.8%)	Shear in the 1-2 plane
	G_{13}	*Msi*	0.5138 (6.4%)	0.4007 (7.3%)	0.4733 (4.3%)	0.5356 (3.3%)	0.4451 (3.7%)	Shear in the 1-3 plane
	G_{23}	*Msi*	0.4962 (5.7%)	0.3884 (5.7%)	0.4802 (3.6%)	0.5392 (3.3%)	0.3487 (7.1%)	Shear in the 2-3 plane
Poissons Ratio	n_{12}		0.153 (5.8%)	0.180 (7.9%)	0.051 (5.2%)	0.054 (6.8%)	0.355 (15.8%)	Tension in the 1-dir
	n_{13}		0.430	0.47	0.52	0.46	0.4500	Compression in the 3-dir
	n_{23}		0.44	*Properties not generated due to balanced lamina*			0.634	Compression in the 3-dir
Strength in the 1, 2, 3 Direction	F_{1t}	*ksi*	63.56 (6.3%)	43.25 (10.9%)	136.3 (5.8%)	151.5 (5.1%)	199.9 (5.3%)	Tension in the 1-dir
	F_{1c}	*ksi*	57.58 (6.7%)	51.01 (9.1%)	80.98 (5.6)	82.27 (7.0%)	82.69 (9.4%)	Compression in the 1-dir
	F_{2t}	*ksi*	58.58 (7.4%)	*Properties not generated due to balanced lamina*			4.629 (15.1%)	Tension in the 2-dir
	F_{2c}	*ksi*	56.56 (9.1%)				18.86 (4.5)	Compression in the 2-dir
	F_{3t} [b]	*ksi*	4.30	4.30	3.70	3.70	3.70	Literature
	F_{3c}	*ksi*	80.73 (5.1%)	65.26 (6.0%)	83.23 minimum	82.63 minimum	21.21 (2.5%)	Compression in the 3-dir
Shear Strength (0.2% Offset)	F_{12}	*ksi*	10.20 (8.3%)	6.463 (8.8%)	6.125 (5.1%)	6.368 (5.0%)	6.267 (6.5%)	Shear in the 1-2 plane
	F_{13}	*ksi*	5.544 (6.9%)	4.590 (8.0%)	6.056 (3.9%)	6.288 (6.0%)	5.358 (4.6%)	Shear in the 1-3 plane
	F_{23}	*ksi*	5.540 (6.6%)	4.464 (7.0%)	6.137 (4.8%)	6.421 (6.8%)	3.131 (10.5%)	Shear in the 2-3 plane
Physical Property			*Mean Value*	*Mean Value*	*Mean Value*	*Mean Value*	*Mean Value*	
Laminate Details	Ply Thickness	*in*	0.021	0.06	0.016	0.021	0.030	
	Fiber Fraction (WF / VF)	*%*	68.2 / 47.0	58.1 / 36.5	62.0 / 50.2	64.2 / 52.5	59.1 / 47.1	
	Plies	*#*	10	4	10	7	4	
	Laminate Thickness	*in*	0.211	0.243	0.157	0.150	0.122	

Note a: Through-thickness tensile modulus data taken as equal to through-thickness compression modulus

Note b: Through-thickness tensile strength data obtained from literature for similar materials

Table F2. Material Property Test Results for Finite Element Modeling (SI Units)

Material Property			E-glass		Carbon			Property Obtained From
			E-LTM 1603	E-LTCFM 3610	C-BX 1200	C-BX 1800	C-LA 1812	
			Biaxial (0/90)	*Biaxial (0/90)*	*Double Bias (±45)*	*Double Bias (±45)*	*Unidirectional (0)*	
			Mean Value	*Mean Value*	*Mean Value*	*Mean Value*	*Mean Value*	
Modulus in the 1, 2, 3 Directions	E_{1t}	*GPa*	24.08	18.82	62.16	67.87	89.22	Tension in the 1-dir
	E_{1c}	*GPa*	24.79	18.54	55.63	59.79	80.19	Compression in the 1-dir
	E_{2t}	*GPa*	22.81	*Properties not generated due to balanced lamina*			6.888	Tension in the 2-dir
	E_{2c}	*GPa*	24.40				7.308	Compression in the 2-dir
	E_{3t} [a]	*GPa*	11.60	9.432	9.832	10.71	7.874	Compression in the 3-dir
	E_{3c}	*GPa*	11.60	9.432	9.832	10.71	7.874	Compression in the 3-dir
Shear Modulus	G_{12}	*GPa*	4.123	2.661	3.178	3.585	3.992	Shear in the 1-2 plane
	G_{13}	*GPa*	3.537	2.758	3.261	3.689	3.068	Shear in the 1-3 plane
	G_{23}	*GPa*	3.420	2.675	3.309	3.716	2.399	Shear in the 2-3 plane
Poissons Ratio	ν_{12}		0.153	0.180	0.051	0.054	0.355	Tension in the 1-dir
	ν_{13}		0.43	0.474	0.522	0.461	0.45	Compression in the 3-dir
	ν_{23}		0.444	*Properties not generated due to balanced lamina*			0.634	Compression in the 3-dir
Strength in the 1, 2, 3 Direction	F_{1t}	*MPa*	438.2	298.2	939.8	1045	1378	Tension in the 1-dir
	F_{1c}	*MPa*	397.0	351.7	558.3	567.2	570.1	Compression in the 1-dir
	F_{2t}	*MPa*	403.9	*Properties not generated due to balanced lamina*			31.92	Tension in the 2-dir
	F_{2c}	*MPa*	390.0				130.0	Compression in the 2-dir
	F_{3t} [b]	*MPa*	29.6	29.6	25.5	25.5	25.5	Literature
	F_{3c}	*MPa*	556.6	450.0	573.9	569.7	146.2	Compression in the 3-dir
Shear Strength (0.2% Offset)	F_{12}	*MPa*	70.33	44.56	42.23	43.91	43.21	Shear in the 1-2 plane
	F_{13}	*MPa*	38.22	31.65	41.75	43.35	36.94	Shear in the 1-3 plane
	F_{23}	*MPa*	38.20	30.78	42.31	44.27	21.59	Shear in the 2-3 plane
Physical Property			*Mean Value*	*Mean Value*	*Mean Value*	*Mean Value*	*Mean Value*	
Laminate Details	Ply Thickness	*mm*	0.537	1.54	0.398	0.544	0.772	
	Fiber Fraction (WF / VF)	*%*	68.2 / 47.0	58.1 / 36.5	62.0 / 50.2	64.2 / 52.5	59.1 / 47.1	
	Plies	*#*	10	4	10	7	4	
	Laminate Thickness	*mm*	5.371	6.179	3.981	3.806	3.089	

Note a: Through-thickness tensile modulus data taken as equal to through-thickness compression modulus

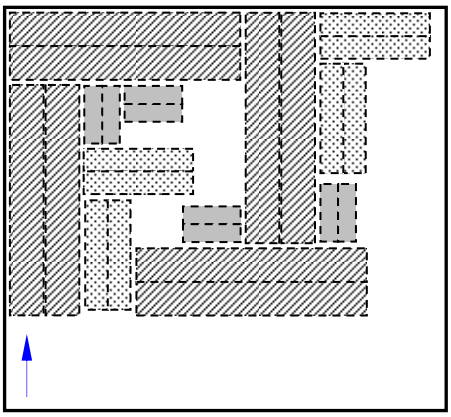
Note b: Through-thickness tensile strength data obtained from literature for similar materials

E-LTM 1603 - Biaxial (0°/90°) *(47 / 37 / 0 / 0 / 16)*

In-Plane Properties

23” x 21” area (25” x 23” panel)

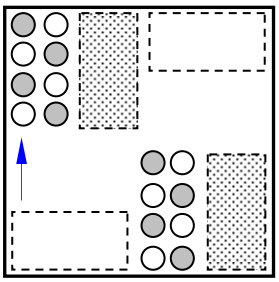
4 specimens/panel – 3 panels required



Through Thickness Properties

14” x 14” area (16” x 16” panel)

4 specimens/panel – 3 panels required



Fracture Properties

Not Required

Thickness	**0.21**	**1.01**
# of Layers	**10**	**48**
50” Roll Feet	**29**	**64**

Test	**Property**
Tension in 1-dir	(E_{1t}, F_{1t}, v_{12})
Tension in 2-dir	(E_{2t}, F_{2t}, v_{21})
Comp. in 1 dir	(E_{1c}, F_{1c}, v_{12})
Comp. in 2-dir	(E_{2c}, F_{2c}, v_{21})
Shear in 12-dir	(G_{12}, F_{12})

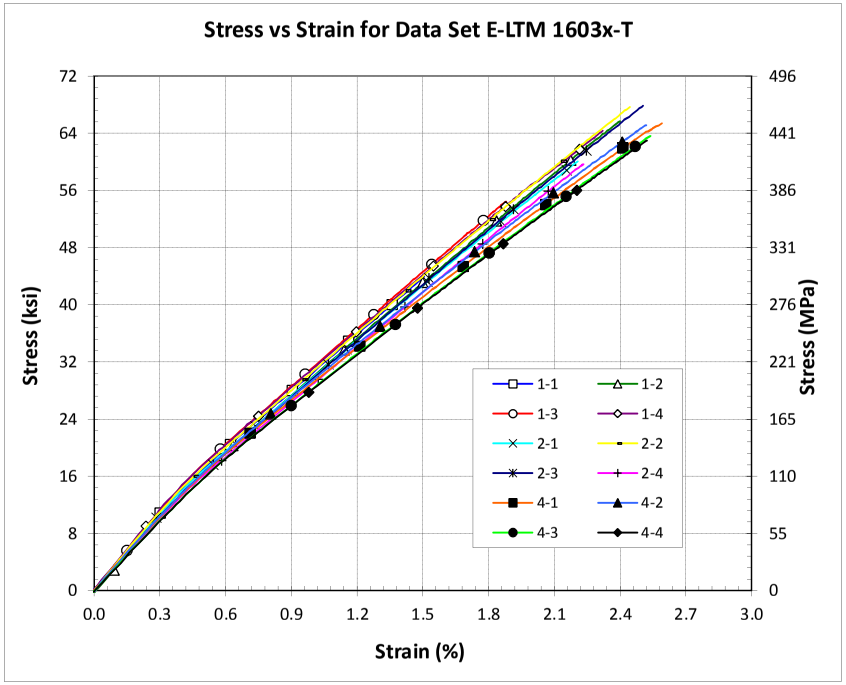
Test	**Property**
Tension in 3-dir	(E_{3t}, F_{3t}, v_{31}, v_{32})
Comp. in 3-dir	(E_{3c}, F_{3c}, v_{31}, v_{32})
Shear in 13-dir	(G_{13}, F_{13})
Shear in 23-dir	(G_{23}, F_{23})

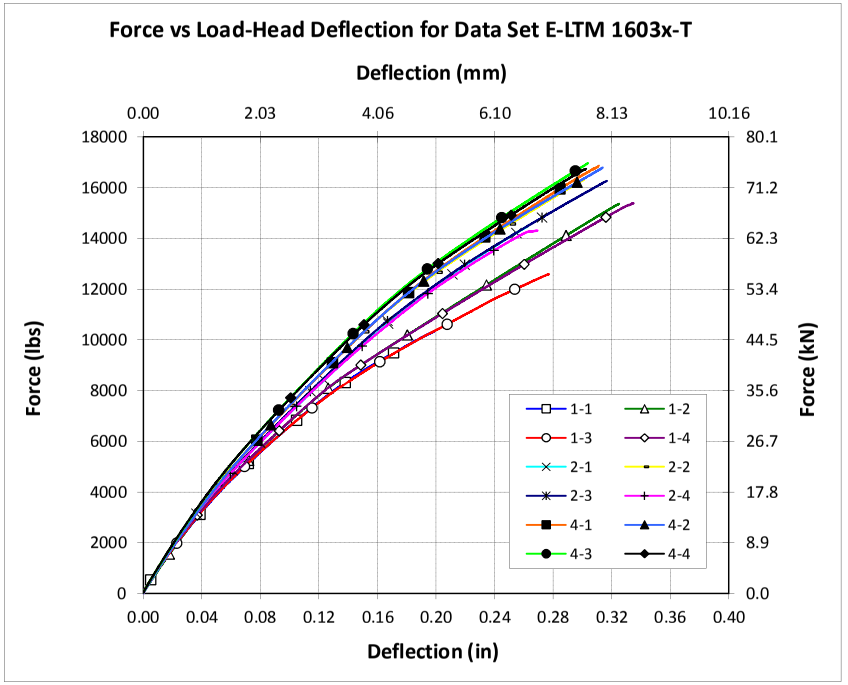
F_{13} & F_{23} are larger than what would be obtained from tests in the 31 and 32 directions

Tension Test Results Summary for the E-LTM 1603x Data Set

Notes	Specimen Number panel-spec.	Specimen Gage Area Dimensions: Width in	Width mm	Thickness in	Thickness mm	Area in²	Area mm²	Failure Load: Aramis lbs.	Aramis kN	Instron lbs.	Instron kN	Strength: Aramis ksi	Aramis MPa	Instron ksi	Instron MPa	Modulus: Aramis Msi	Aramis GPa	Failure Strain %	Poisson's Ratio ν_{12}	Strain Range x10⁻⁶
1	1-1	1.155	29.34	0.2034	5.167	0.2350	151.6	10,327	45.94	10,329	45.95	43.95	303.0	**43.96**	**303.1**	**3.578**	**24.67**	1.507	0.1754	992 to 2999
	1-2	1.155	29.34	0.2025	5.142	0.2338	150.9	15,348	68.27	15,376	68.39	65.63	452.5	**65.75**	**453.4**	**3.486**	**24.03**	2.399	0.1510	988 to 2993
	1-3	1.153	29.29	0.2005	5.093	0.2312	149.2	12,579	55.96	12,599	56.04	54.41	375.1	**54.49**	**375.7**	**3.697**	**25.49**	1.880		
	1-4	1.153	29.28	0.2071	5.261	0.2388	154.1	15,370	68.37	15,393	68.47	64.37	443.8	**64.46**	**444.5**	**3.748**	**25.85**	2.321	0.1362	985 to 2998
	2-1	1.152	29.27	0.2085	5.295	0.2402	155.0	14,425	64.17	14,469	64.36	60.05	414.0	**60.23**	**415.3**	**3.593**	**24.77**	2.207	0.1596	997 to 2994
	2-2	1.155	29.33	0.2082	5.289	0.2404	155.1	16,271	72.38	16,344	72.70	67.67	466.6	**67.97**	**468.7**	**3.582**	**24.70**	2.445		
	2-3	1.156	29.36	0.2066	5.248	0.2388	154.1	16,205	72.08	16,268	72.36	67.85	467.8	**68.11**	**469.6**	**3.475**	**23.96**	2.505	0.1559	986 to 2985
	2-4	1.154	29.31	0.2073	5.266	0.2392	154.3	14,271	63.48	14,317	63.68	59.67	411.4	**59.86**	**412.7**	**3.388**	**23.36**	2.233		
	4-1	1.156	29.37	0.2223	5.647	0.2570	165.8	16,809	74.77	16,872	75.05	65.39	450.9	**65.64**	**452.6**	**3.353**	**23.12**	2.591	0.1524	987 to 2993
	4-2	1.160	29.45	0.2210	5.613	0.2562	165.3	16,688	74.23	16,794	74.70	65.13	449.1	**65.54**	**451.9**	**3.425**	**23.62**	2.519		
	4-3	1.168	29.65	0.2279	5.788	0.2660	171.6	16,919	75.26	16,978	75.52	63.59	438.5	**63.82**	**440.0**	**3.320**	**22.89**	2.539	0.1599	998 to 2983
	4-4	1.165	29.60	0.2271	5.768	0.2646	170.7	16,666	74.14	16,743	74.48	62.98	434.3	**63.27**	**436.3**	**3.346**	**23.07**	2.523		
	MEAN	***1.157***	***29.39***	***0.2126***	***5.401***	***0.2460***	***158.7***	***15,596***	***69.37***	***15,650***	***69.61***	***63.34***	***436.7***	***63.56***	***438.2***	***3.492***	***24.08***	***2.378***	***0.1525***	
	COV	***0.44***	***0.44***	***4.67***	***4.67***	***5.07***	***5.07***	***8.77***	***8.77***	***8.86***	***8.86***	***6.26***	***6.26***	***6.32***	***6.32***	***4.17***	***4.17***	***8.76***	***5.75***	

Note 1: Specimen 1-1 was not aligned in the grips properly, which resulted in a premature failure of the specimen. Therefore, it was not included in the calculations for the Mean.

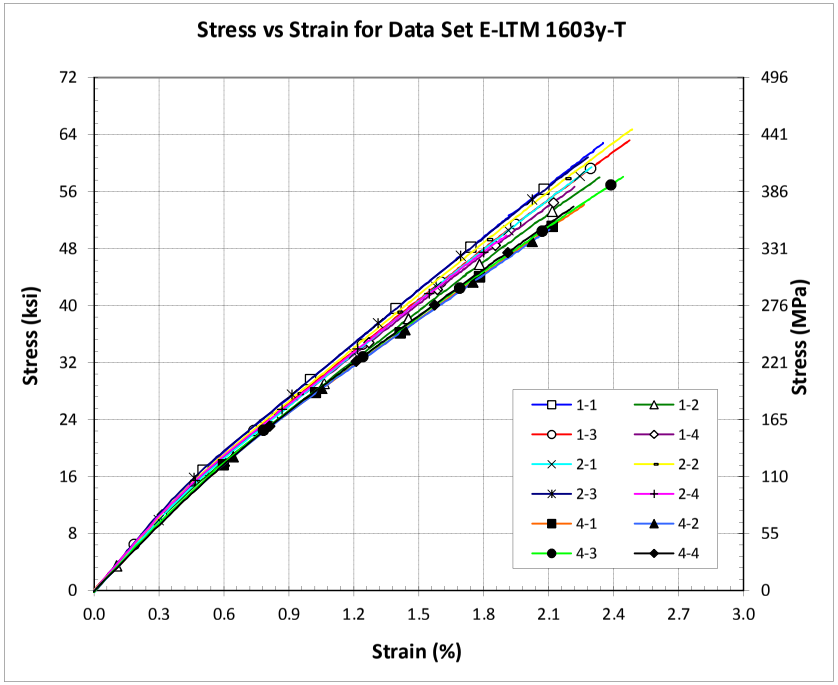


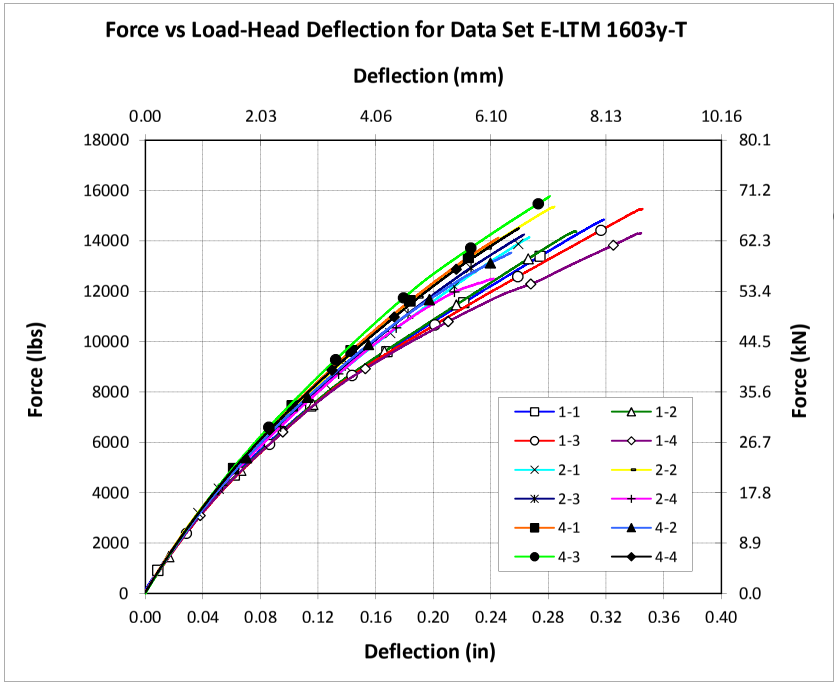


Tension Test Results Summary for the E-LTM 1603y Data Set

Notes	Specimen Number	Specimen Gage Area Dimensions						Failure Load				Strength				Modulus		Failure Strain	
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis		Aramis	Strain Gage
	panel-spec.	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	%
	1-1	1.156	29.36	0.2043	5.189	0.2361	152.4	14,843	66.02	14,846	66.04	62.85	433.4	**62.87**	**433.4**	**3.531**	**24.35**	2.351	2.316
	1-2	1.157	29.38	0.2143	5.444	0.2479	159.9	14,370	63.92	14,369	63.91	57.97	399.7	**57.97**	**399.7**	**3.240**	**22.34**	2.335	
	1-3	1.157	29.40	0.2085	5.295	0.2413	155.7	15,249	67.83	15,266	67.91	63.20	435.8	**63.28**	**436.3**	**3.460**	**23.86**	2.474	2.443
	1-4	1.155	29.34	0.2184	5.547	0.2523	162.7	14,304	63.63	14,307	63.64	56.71	391.0	**56.72**	**391.0**	**3.363**	**23.19**	2.220	
	2-1	1.154	29.32	0.2058	5.227	0.2375	153.2	14,117	62.80	14,145	62.92	59.43	409.8	**59.55**	**410.6**	**3.364**	**23.20**	2.298	2.246
	2-2	1.153	29.29	0.2049	5.204	0.2362	152.4	15,293	68.03	15,359	68.32	64.74	446.4	**65.02**	**448.3**	**3.402**	**23.46**	2.486	2.367
	2-3	1.157	29.39	0.2019	5.127	0.2336	150.7	14,205	63.19	14,261	63.44	60.82	419.3	**61.06**	**421.0**	**3.557**	**24.53**	2.281	
1	2-4	1.157	29.38	0.2157	5.478	0.2494	160.9	12,437	55.32	12,504	55.62	49.86	343.8	**50.13**	**345.7**	**3.434**	**23.67**	1.905	1.787
	4-1	1.150	29.22	0.2255	5.727	0.2594	167.3	14,052	62.50	14,126	62.84	54.18	373.5	**54.46**	**375.5**	**3.159**	**21.78**	2.264	
	4-2	1.150	29.21	0.2311	5.869	0.2657	171.4	13,469	59.91	13,537	60.21	50.69	349.5	**50.94**	**351.2**	**3.098**	**21.36**	2.104	
	4-3	1.166	29.62	0.2320	5.893	0.2706	174.6	15,710	69.88	15,777	70.18	58.07	400.4	**58.31**	**402.1**	**3.174**	**21.88**	2.444	2.544
	4-4	1.160	29.46	0.2307	5.860	0.2675	172.6	14,425	64.17	14,497	64.49	53.92	371.7	**54.19**	**373.6**	**3.050**	**21.03**	2.215	
	MEAN	***1.156***	***29.36***	***0.2161***	***5.489***	***0.2498***	***161.2***	***14,549***	***64.72***	***14,590***	***64.90***	***58.42***	***402.8***	***58.58***	***403.9***	***3.309***	***22.81***	***2.316***	***2.383***
	COV	***0.39***	***0.39***	***5.51***	***5.51***	***5.60***	***5.60***	***4.51***	***4.51***	***4.49***	***4.49***	***7.47***	***7.47***	***7.39***	***7.39***	***5.28***	***5.28***	***5.12***	***4.83***

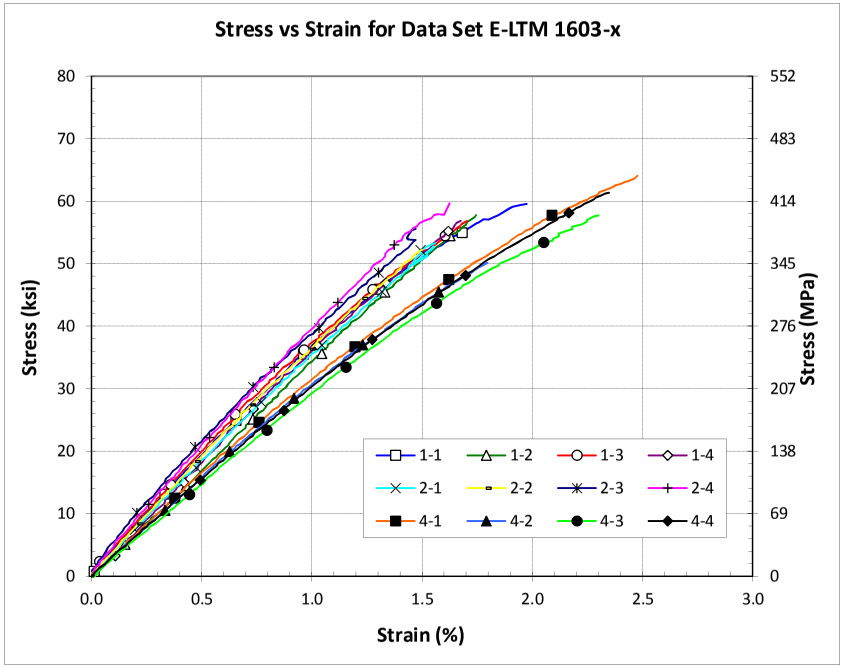
Note 1: The specimen failed in the grip region; therefore, it was not included in the calculations for the Mean.

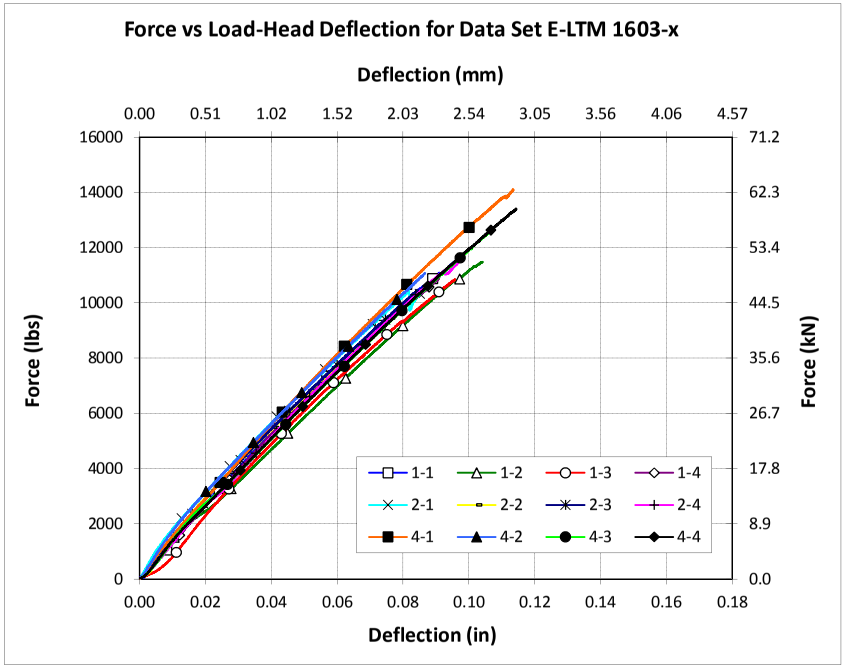




Compression Test Results Summary for the E-LTM 1603-x Data Set

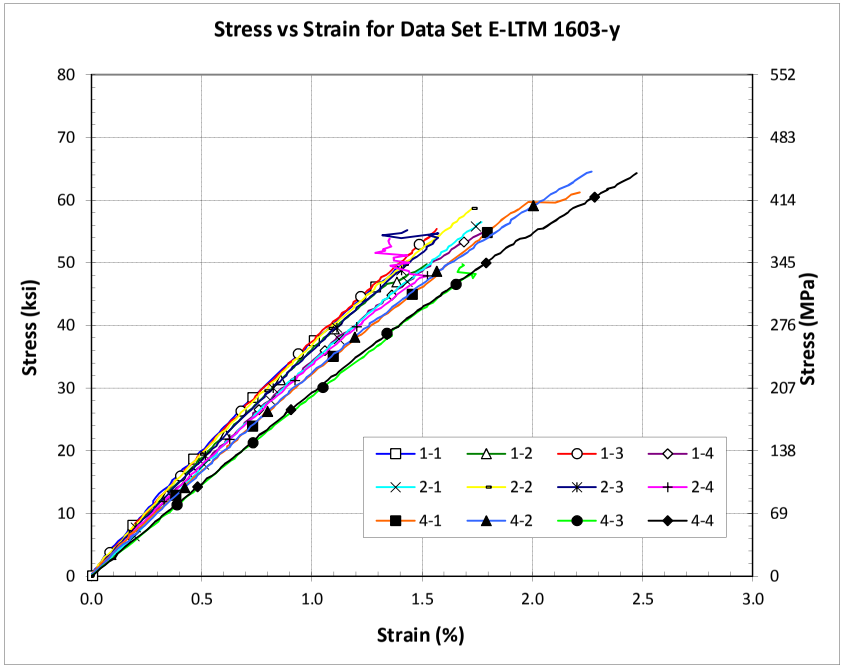
Notes	Specimen Number	Specimen Dimensions						Failure Load				Strength				Modulus		Failure		
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis		Strain	Local	Type
	#	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	Gage?	Code
	1-1	0.9624	24.44	0.2011	5.107	0.1935	124.8	11,523	51.26	11,605	51.62	59.55	410.6	**59.98**	**413.5**	**3.817**	**26.32**	1.975		
	1-2	0.9630	24.46	0.2056	5.223	0.1980	127.8	11,435	50.86	11,482	51.08	57.75	398.1	**57.99**	**399.8**	**3.418**	**23.57**	1.745		
	1-3	0.9603	24.39	0.1975	5.017	0.1897	122.4	10,776	47.93	10,854	48.28	56.81	391.7	**57.22**	**394.5**	**3.820**	**26.34**	1.704		
	1-4	0.9596	24.37	0.1979	5.026	0.1899	122.5	10,798	48.03	10,915	48.55	56.86	392.1	**57.48**	**396.3**	**3.826**	**26.38**	1.676		
	2-1	0.9598	24.38	0.2040	5.182	0.1958	126.3	10,424	46.37	10,589	47.10	53.24	367.1	**54.08**	**372.9**	**3.673**	**25.33**	1.559		
	2-2	0.9563	24.29	0.1991	5.057	0.1904	122.8	9,941	44.22	10,080	44.84	52.22	360.0	**52.95**	**365.1**	**3.874**	**26.71**	1.499		
	2-3	0.9554	24.27	0.2007	5.097	0.1917	123.7	10,655	47.40	10,737	47.76	55.57	383.2	**56.00**	**386.1**	**4.199**	**28.95**	1.471		
	2-4	0.9533	24.21	0.2001	5.081	0.1907	123.0	11,380	50.62	11,492	51.12	59.67	411.4	**60.26**	**415.5**	**4.279**	**29.50**	1.625		
	4-1	0.9663	24.54	0.2267	5.757	0.2190	141.3	14,027	62.40	14,105	62.74	64.05	441.6	**64.40**	**444.1**	**3.284**	**22.65**	2.476		
	4-2	0.9665	24.55	0.2263	5.747	0.2187	141.1	10,962	48.76	11,077	49.27	50.13	345.6	**50.65**	**349.2**	**3.020**	**20.82**	1.796		
	4-3	0.9656	24.53	0.2236	5.679	0.2159	139.3	12,456	55.41	12,579	55.95	57.69	397.8	**58.26**	**401.7**	**2.909**	**20.06**	2.301		
	4-4	0.9619	24.43	0.2260	5.740	0.2174	140.2	13,335	59.32	13,411	59.66	61.34	422.9	**61.69**	**425.4**	**3.022**	**20.83**	2.348		
	MEAN	***0.9608***	***24.41***	***0.2090***	***5.309***	***0.2009***	***129.6***	***11,476***	***51.05***	***11,577***	***51.50***	***57.07***	***393.5***	***57.58***	***397.0***	***3.595***	***24.79***	***1.848***		
	COV	***0.45***	***0.45***	***5.97***	***5.97***	***6.33***	***6.33***	***10.60***	***10.60***	***10.39***	***10.39***	***6.88***	***6.88***	***6.65***	***6.65***	***12.79***	***12.79***	***18.80***		

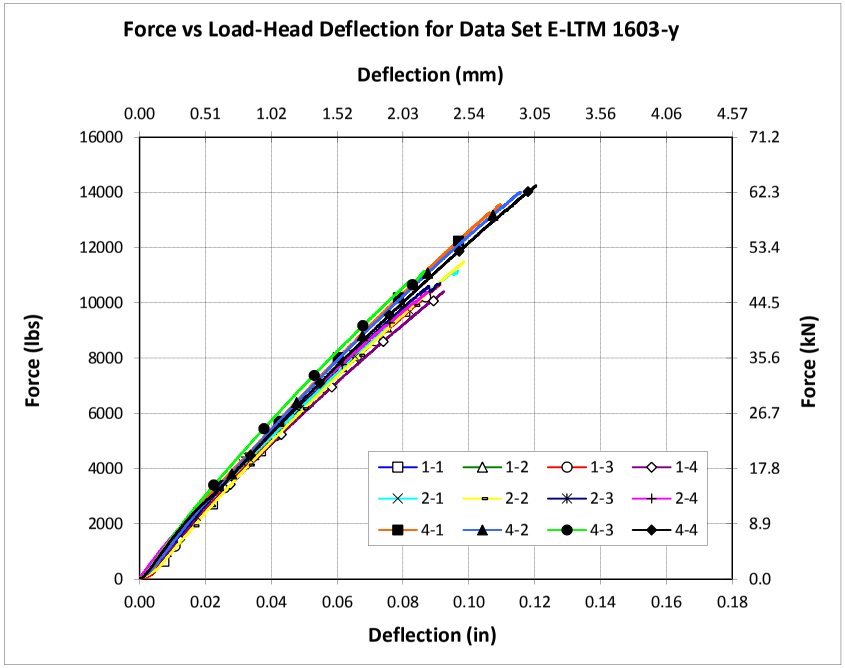




Compression Test Results Summary for the E-LTM 1603-y Test Series

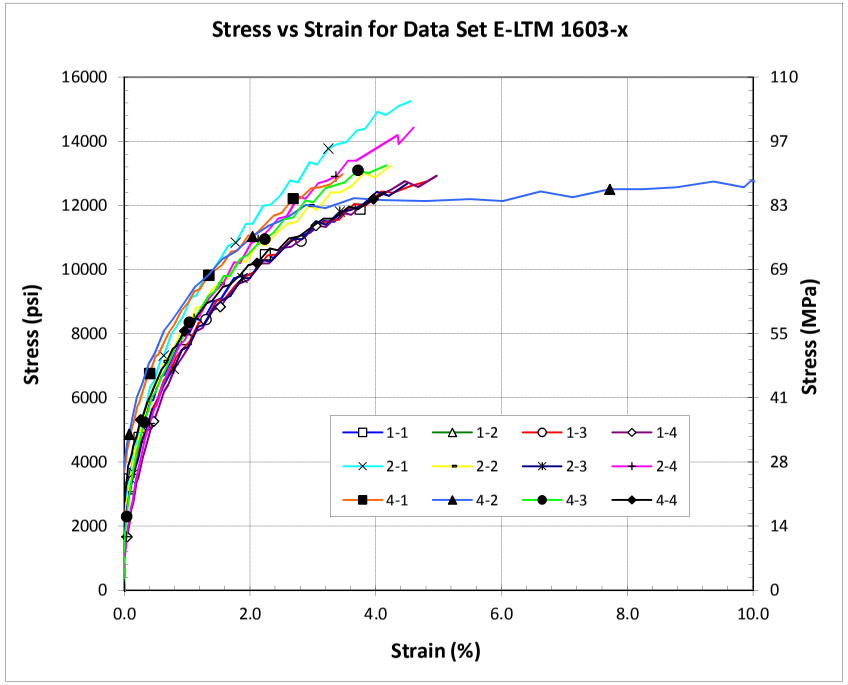
Notes	Specimen Number #	Specimen Dimensions: Width in	Width mm	Thickness in	Thickness mm	Area in²	Area mm²	Failure Load: Aramis lbs.	Aramis kN	Instron lbs.	Instron kN	Strength: Aramis ksi	Aramis MPa	Instron ksi	Instron MPa	Modulus: Aramis Msi	Aramis GPa	Failure: Strain %	Local Gage?	Type Code
	1-1	0.9568	24.30	0.2030	5.157	0.1942	125.3	9,754	43.39	9,814	43.65	50.22	346.2	**50.52**	**348.3**	**4.071**	**28.07**	1.432		
	1-2	0.9558	24.28	0.2006	5.095	0.1917	123.7	9,545	42.46	9,640	42.88	49.79	343.3	**50.29**	**346.7**	**3.745**	**25.82**	1.522		
	1-3	0.9529	24.20	0.2008	5.101	0.1914	123.5	10,600	47.15	10,675	47.49	55.39	381.9	**55.78**	**384.6**	**3.984**	**27.47**	1.567		
	1-4	0.9539	24.23	0.1981	5.031	0.1889	121.9	10,347	46.03	10,417	46.34	54.76	377.6	**55.13**	**380.1**	**3.612**	**24.91**	1.772		
	2-1	0.9578	24.33	0.2044	5.191	0.1957	126.3	11,050	49.15	11,151	49.60	56.46	389.3	**56.97**	**392.8**	**3.520**	**24.27**	1.770		
	2-2	0.9558	24.28	0.2038	5.176	0.1948	125.7	11,424	50.82	11,499	51.15	58.66	404.4	**59.04**	**407.1**	**4.057**	**27.98**	1.727		
	2-3	0.9531	24.21	0.2018	5.126	0.1923	124.1	10,622	47.25	10,714	47.66	55.22	380.7	**55.70**	**384.0**	**3.667**	**25.29**	1.433		
	2-4	0.9544	24.24	0.2014	5.115	0.1922	124.0	10,347	46.03	10,388	46.21	53.84	371.2	**54.05**	**372.7**	**3.583**	**24.71**	1.353		
	4-1	0.9655	24.52	0.2282	5.797	0.2204	142.2	13,489	60.00	13,564	60.34	61.21	422.0	**61.55**	**424.4**	**3.197**	**22.04**	2.215		
	4-2	0.9665	24.55	0.2236	5.680	0.2161	139.4	13,950	62.05	14,019	62.36	64.54	445.0	**64.86**	**447.2**	**3.164**	**21.82**	2.270		
	4-3	0.9684	24.60	0.2296	5.832	0.2224	143.5	11,072	49.25	11,160	49.64	49.80	343.3	**50.19**	**346.1**	**2.797**	**19.29**	1.683		
	4-4	0.9658	24.53	0.2283	5.800	0.2205	142.3	14,181	63.08	14,247	63.37	64.31	443.4	**64.61**	**445.4**	**3.074**	**21.20**	2.474		
	MEAN	***0.9589***	***24.36***	***0.2103***	***5.342***	***0.2017***	***130.1***	***11,365***	***50.55***	***11,441***	***50.89***	***56.18***	***387.4***	***56.56***	***390.0***	***3.539***	***24.40***	***1.768***		
	COV	***0.61***	***0.61***	***6.11***	***6.11***	***6.73***	***6.73***	***14.14***	***14.14***	***14.03***	***14.03***	***9.20***	***9.20***	***9.09***	***9.09***	***11.56***	***11.56***	***20.58***		

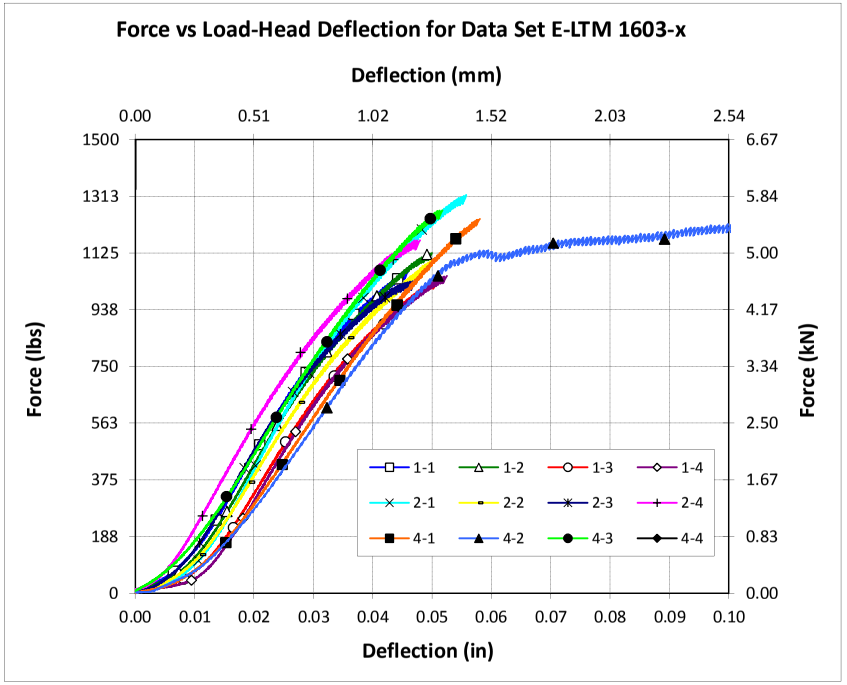




Shear Test Results Summary for the E-LTM 1603-x Data Set

Notes	Specimen Number #	V-Notch Dimensions Width in	Width mm	Thickness in	Thickness mm	Area in²	Area mm²	Failure Load Aramis lbs.	Failure Load Aramis kN	Failure Load Instron lbs.	Failure Load Instron kN	Strength Aramis ksi	Strength Aramis MPa	Strength Instron ksi	Strength Instron MPa	Modulus Aramis ksi	Modulus Aramis Mpa	0.2% Offset Strain %	0.2% Offset Strength ksi	0.2% Offset Strength MPa
	1-1	0.4055	10.30	0.2080	5.283	0.0843	54.42	1,050	4.669	1,062	4.726	12.45	85.81	**12.60**	**86.85**	**0.5739**	**3.957**	1.890	9.80	67.57
	1-2	0.4038	10.26	0.2056	5.222	0.0830	53.55	1,111	4.943	1,124	5.000	13.39	92.30	**13.54**	**93.37**					
	1-3	0.4010	10.19	0.1988	5.050	0.0797	51.43	1,016	4.520	1,030	4.583	12.75	87.89	**12.92**	**89.10**	**0.5659**	**3.902**	1.930	9.78	67.43
	1-4	0.3990	10.13	0.2019	5.129	0.0806	51.98	1,041	4.632	1,049	4.668	12.93	89.12	**13.03**	**89.81**	**0.6636**	**4.576**	1.531	8.84	60.95
	2-1	0.4078	10.36	0.2078	5.279	0.0847	54.67	1,293	5.750	1,317	5.859	15.25	105.17	**15.54**	**107.16**	**0.6852**	**4.725**	1.780	10.90	75.16
	2-2	0.4048	10.28	0.2041	5.184	0.0826	53.29	1,094	4.868	1,100	4.891	13.25	91.35	**13.31**	**91.78**	**0.5947**	**4.100**	1.900	10.25	70.67
	2-3	0.4003	10.17	0.2020	5.131	0.0809	52.16	1,025	4.558	1,032	4.590	12.67	87.37	**12.76**	**87.98**	**0.5805**	**4.003**	1.880	9.74	67.14
	2-4	0.4013	10.19	0.2006	5.094	0.0805	51.92	1,161	5.166	1,167	5.192	14.43	99.51	**14.51**	**100.01**	**0.6907**	**4.762**	1.590	9.60	66.19
	4-1	0.4110	10.44	0.2303	5.849	0.0946	61.06	1,228	5.464	1,238	5.507	12.98	89.49	**13.08**	**90.20**	**0.4706**	**3.245**	2.800	12.20	84.12
	4-2	0.4115	10.45	0.2220	5.638	0.0913	58.92	1,231	5.477	1,238	5.505	13.48	92.94	**13.55**	**93.42**	**0.4808**	**3.315**	2.600	11.60	79.98
	4-3	0.4073	10.34	0.2330	5.917	0.0949	61.21	1,256	5.588	1,266	5.632	13.24	91.31	**13.35**	**92.02**	**0.6349**	**4.378**	1.809	10.20	70.33
	4-4	0.4093	10.39	0.2220	5.639	0.0909	58.62	1,128	5.017	1,140	5.073	12.41	85.59	**12.55**	**86.54**	**0.5288**	**3.646**	2.145	10.26	70.74
	MEAN	***0.4052***	***10.29***	***0.2113***	***5.368***	***0.0857***	***55.27***	***1,136***	***5.054***	***1,147***	***5.102***	***13.27***	***91.49***	***13.39***	***92.35***	***0.5881***	***4.055***	***1.987***	***10.29***	***70.94***
	COV	***1.05***	***1.05***	***5.73***	***5.73***	***6.63***	***6.63***	***8.51***	***8.51***	***8.58***	***8.58***	***6.26***	***6.26***	***6.41***	***6.41***	***12.89***	***12.89***	***19.71***	***9.29***	***9.29***





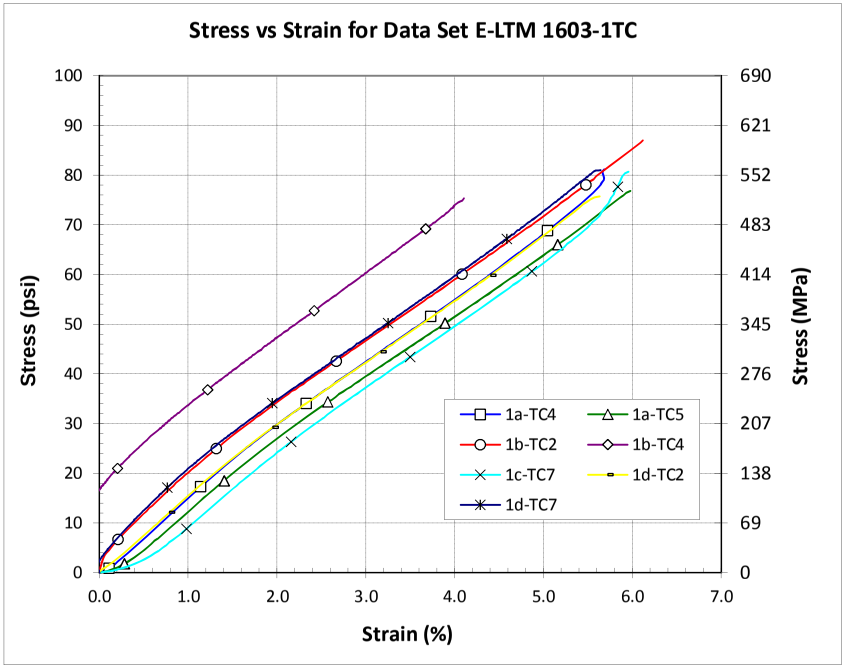
Through-Thickness Compression Test Results Summary for the E-LTM 1603-1 Data Set

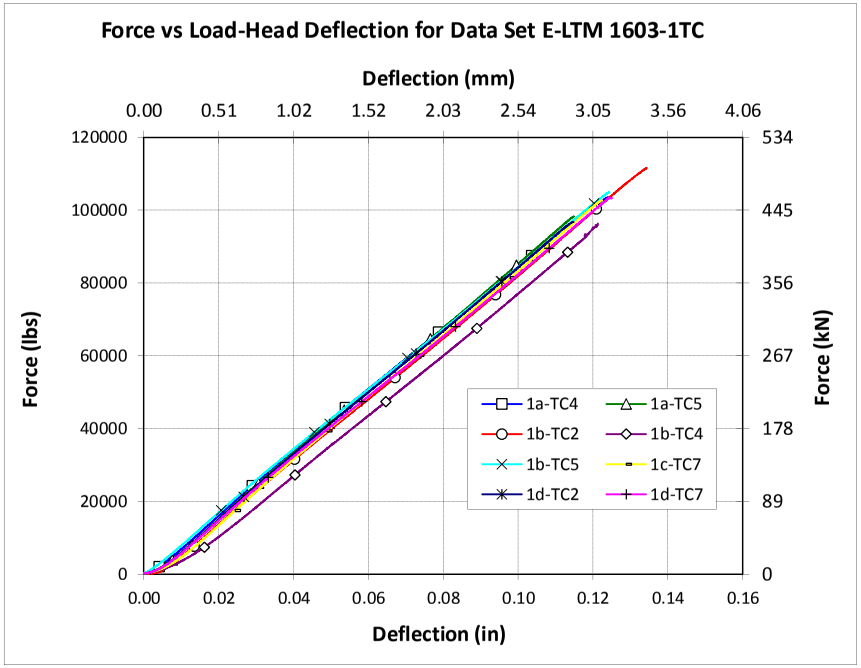
Notes	Specimen Number #	Specimen Dimensions: Diameter in	Diameter mm	Thickness in	Thickness mm	Area in^2	Area mm^2	Failure Load: Aramis lbs.	Aramis kN	Instron lbs.	Instron kN	Strength: Aramis ksi	Aramis MPa	Instron ksi	Instron MPa	Modulus: Aramis Msi	Aramis GPa	Failure Strain %	Poisson's ν_{31}	Poisson's ν_{32}
2	1a-TC4	1.275	32.38	0.9583	24.34	1.276	823.4	103,492	460.4	103,556	460.6	81.09	559.1	**81.14**	**559.4**	**1.638**	**11.29**	5.685		
2	1a-TC5	1.277	32.42	0.9592	24.36	1.280	825.7	98,268	437.1	98,267	437.1	76.79	529.4	**76.78**	**529.4**	**1.545**	**10.65**	5.978		
2	1b-TC2	1.275	32.39	0.9665	24.55	1.277	823.7	111,025	493.9	111,635	496.6	86.96	599.6	**87.44**	**602.8**	**1.689**	**11.65**	6.119		
2, 3	1b-TC4	1.274	32.37	0.9665	24.55	1.275	822.9	96,026	427.1	96,318	428.4	75.29	519.1	**75.52**	**520.7**	**1.603**	**11.05**	4.106		
1, 2, 3	1b-TC5	1.275	32.39	0.9667	24.55	1.277	824.1			104,948	466.8			**82.16**	**566.4**					
2, 3, error	1c-TC5	1.278	32.47	0.9595	24.37	1.283	828.0	28,243	125.6	28,294	125.9	22.01	151.7	**22.05**	**152.0**				0.3109	-0.0021
1	1c-TC7	1.274	32.35	0.9600	24.38	1.274	821.9	102,722	456.9	102,725	456.9	80.63	556.0	**80.64**	**556.0**	**1.567**	**10.80**	5.955		
1	1d-TC2	1.275	32.39	0.9687	24.60	1.277	823.8	96,673	430.0	96,787	430.5	75.71	522.0	**75.80**	**522.6**	**1.596**	**11.01**	5.632		
2, 3	1d-TC7	1.274	32.37	0.9688	24.61	1.276	823.0	103,275	459.4	103,332	459.6	80.96	558.2	**81.01**	**558.5**	**1.728**	**11.92**	5.644	0.2043	0.2476
Panel 1	***MEAN***	***1.275***	***32.38***	***0.9638***	***24.48***	***1.277***	***823.6***	***102,576***	***456.3***	***103,036***	***458.3***	***80.36***	***554.0***	***80.71***	***556.5***	***1.627***	***11.22***	***5.588***	***0.2043***	***0.2476***
	COV	***0.07***	***0.07***	***0.49***	***0.49***	***0.15***	***0.15***	***4.9***	***4.9***	***4.7***	***4.7***	***4.9***	***4.9***	***4.7***	***4.7***	***4.4***	***4.4***	***12.2***	-	-
Panels 1 & 2	***MEAN***	***1.274***	***32.37***	***0.9477***	***24.07***	***1.276***	***823.0***	***102,675***	***456.7***	***102,985***	***458.1***	***80.50***	***555.0***	***80.73***	***556.6***	***1.682***	***11.60***	***5.753***	***0.2012***	***0.2109***
	COV	***0.14***	***0.14***	***4.04***	***4.04***	***0.28***	***0.28***	***5.3***	***5.3***	***5.2***	***5.2***	***5.2***	***5.2***	***5.1***	***5.1***	***5.2***	***5.2***	***5.3***	***5.0***	***12.5***

Note 1: Aramis pattern on the 1-direction

Note 2: Aramis pattern on the 2-direction

Note 3: Load mod





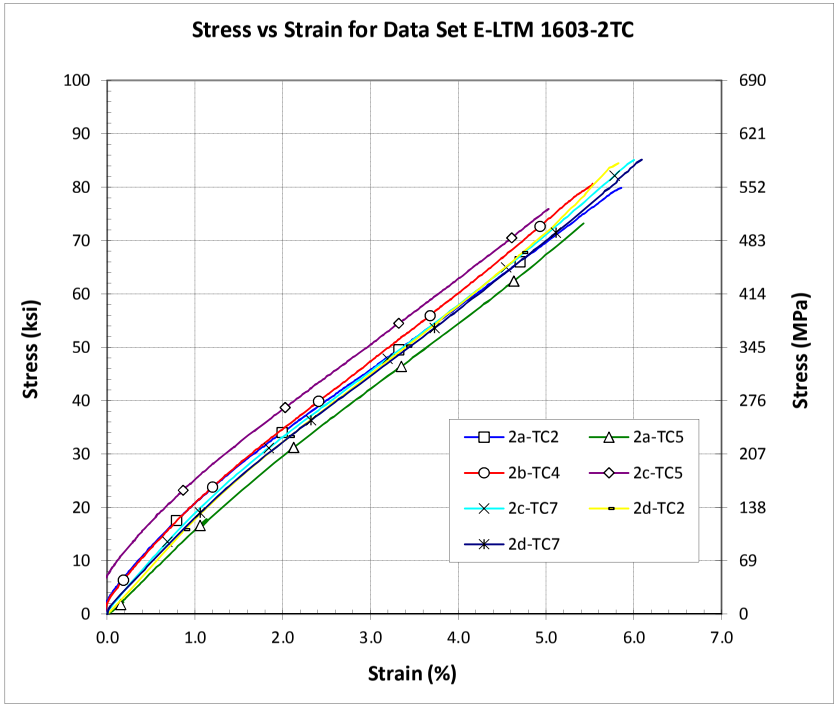
Through-Thickness Compression Test Results Summary for the E-LTM 1603-2 Data Set

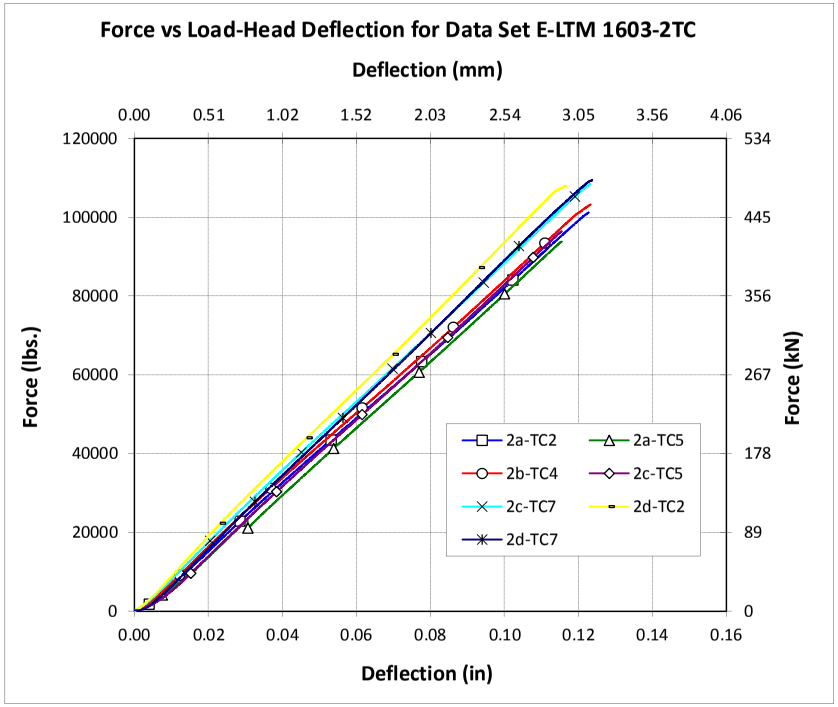
Notes	Specimen Number	Specimen Dimensions						Failure Load				Strength				Modulus		Failure Strain	Poisson's	
		Diameter		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis			ν_{31}	ν_{32}
	panel-spec.	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%		
2, 3	2a-TC2	1.270	32.26	0.9782	24.85	1.267	817.6	101,186	450.1	101,172	450.0	79.85	550.5	**79.83**	**550.4**	**1.703**	**11.74**	5.858	0.2023	0.1849
1	2a-TC5	1.275	32.39	0.9792	24.87	1.277	823.7	93,467	415.8	93,833	417.4	73.21	504.7	**73.49**	**506.7**	**1.636**	**11.28**	5.430		
DNF Error	2b-TC2	1.276	32.41	0.9710	24.66	1.279	825.2	43,600	193.9	43,742	194.6	34.09	235.0	**34.20**	**235.8**	**1.172**	**8.08**	3.263		
2, 3	2b-TC4	1.276	32.40	0.9705	24.65	1.278	824.4	103,069	458.5	103,233	459.2	80.66	556.2	**80.79**	**557.0**	**1.787**	**12.32**	5.530	0.1872	0.2084
2, 3	2c-TC5	1.271	32.29	0.9308	23.64	1.270	819.1	96,386	428.7	96,422	428.9	75.92	523.4	**75.95**	**523.6**	**1.637**	**11.29**	5.033	0.2110	0.2028
1	2c-TC7	1.273	32.33	0.9300	23.62	1.273	821.1	108,257	481.5	108,434	482.3	85.06	586.4	**85.20**	**587.4**	**1.806**	**12.45**	6.006		
2	2d-TC2	1.276	32.40	0.8598	21.84	1.278	824.5	107,982	480.3	108,043	480.6	84.50	582.6	**84.55**	**582.9**	**1.802**	**12.42**	5.826		
1	2d-TC7	1.277	32.43	0.8607	21.86	1.280	825.8	108,971	484.7	109,399	486.6	85.14	587.0	**85.47**	**589.3**	**1.735**	**11.96**	6.093		
	MEAN	***1.274***	***32.36***	***0.9327***	***23.69***	***1.275***	***822.4***	***102,760***	***457.1***	***102,934***	***457.9***	***80.62***	***555.8***	***80.75***	***556.8***	***1.729***	***11.92***	***5.380***	***0.2002***	***0.1987***
	COV	***0.18***	***0.18***	***5.26***	***5.26***	***0.36***	***0.36***	***6.0***	***6.0***	***6.0***	***6.0***	***5.8***	***5.8***	***5.8***	***5.8***	***4.3***	***4.3***	***17.1***	***6.0***	***6.2***

Note 1: Aramis pattern on the 1-direction

Note 2: Aramis pattern on the 2-direction

Note 3: Load mod



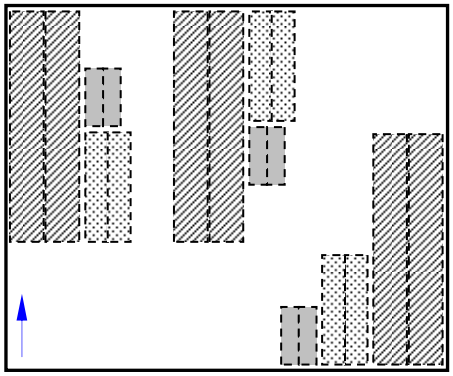


E-LTM 3610 - Biaxial (0°/90°) *(41 / 39 / 0 / 0 / 20)*

In-Plane Properties

23” x 19” area (25” x 21” panel)

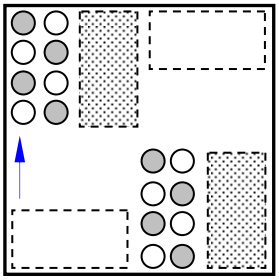
6 specimens/panel – 2 panels required



Through Thickness Properties

14” x 14” area (16” x 16” panel)

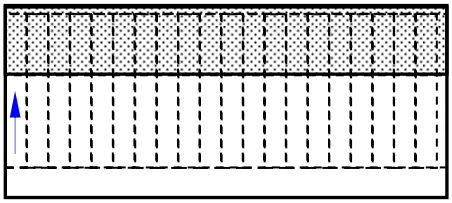
6 specimens/panel – 2 panels required



Fracture Properties

48” x 10” area (50” x 12” panel)

40 specimens/panel – 4 panels required



Thick ness	**0.20**	**1.00**	**0.20**
# of Layers	**4**	**20**	**4**
50” Roll feet	**7**	**18**	**16**

Test	**Property**
Tension in 1-dir	(E_{1t}, F_{1t}, v_{12})
Comp. in 1 dir	(E_{1c}, F_{1c}, v_{12})
Shear in 12-dir	(G_{12}, F_{12})

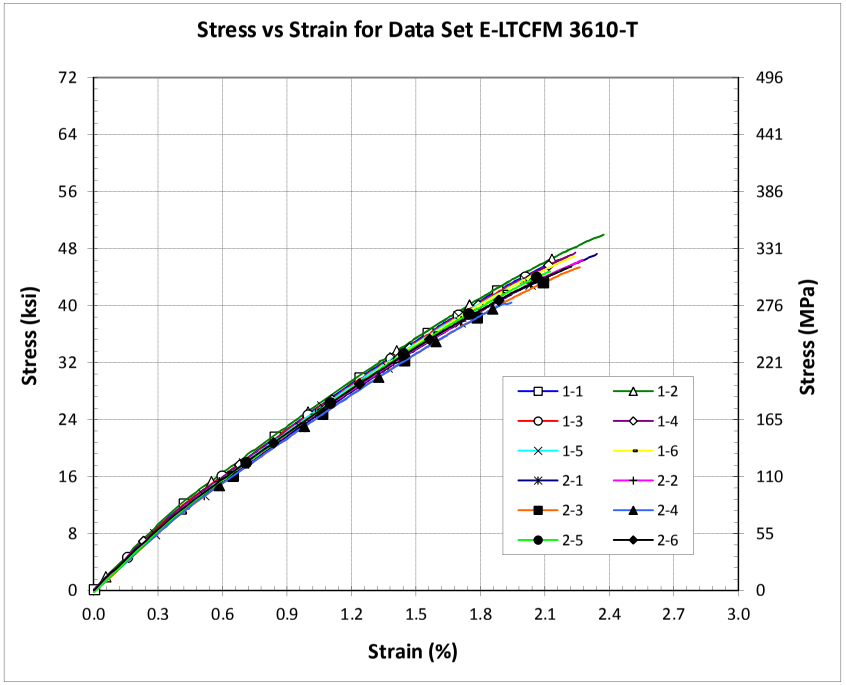
Test	**Property**
Tension in 3-dir	(E_{3t}, F_{3t}, v_{31}, v_{32})
Comp. in 3-dir	(E_{3c}, F_{3c}, v_{31}, v_{32})
Shear in 13-dir	(G_{13}, F_{13})
Shear in 23-dir	(G_{23}, F_{23})

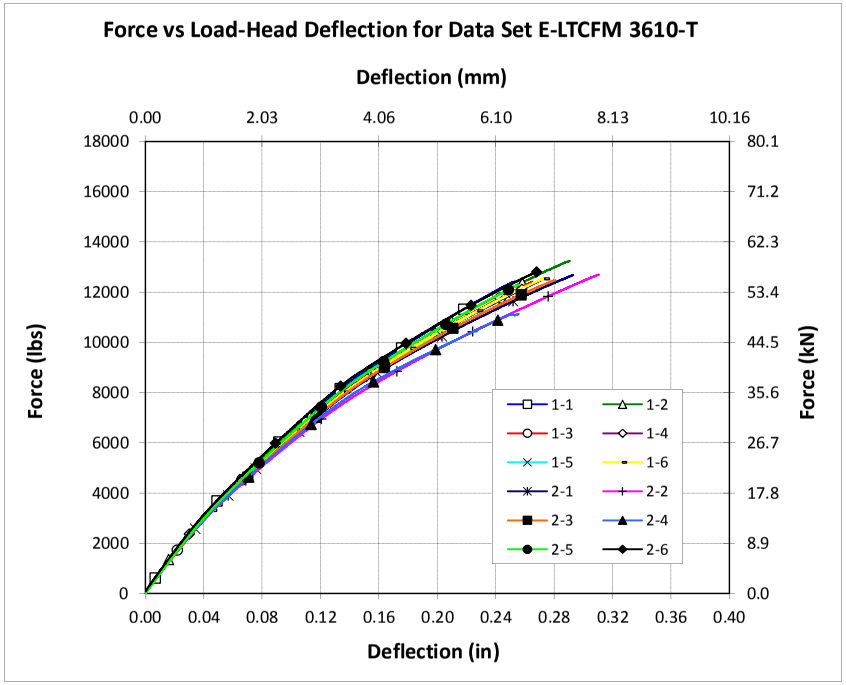
F_{13} & F_{23} are larger than what would be obtained from tests in the 31 and 32 directions

Test	**Property**
Mode-I	($G_{1c\ onset}$, $G_{1c\ propagation}$)
Mode-II	($G_{2c\ onset}$, $G_{2c\ propagation}$)

Tension Test Results Summary for the E-LTCFM 3610 Data Set

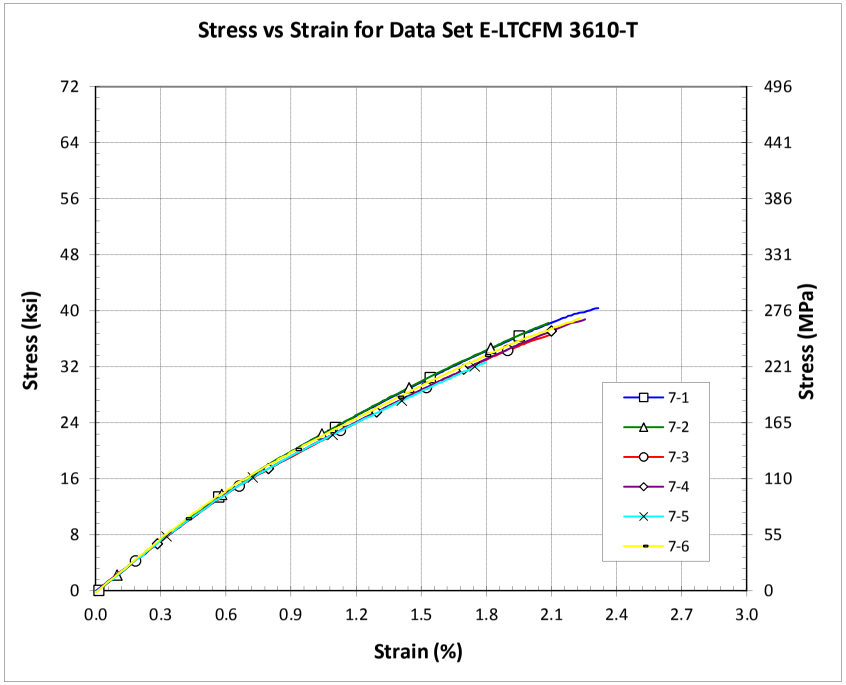
Notes	Specimen Number	Specimen Gage Area Dimensions						Failure Load				Strength				Modulus		Failure Strain	Poisson's Ratio	
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis			ν_{12}	Strain Range
	panel-spec.	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%		x 10^{-6}
	1-1	1.156	29.37	0.2304	5.853	0.2664	171.9	12,382	55.08	12,431	55.30	46.47	320.4	**46.66**	**321.7**	**2.932**	**20.22**	2.179		
	1-2	1.153	29.30	0.2300	5.842	0.2653	171.2	13,249	58.93	13,250	58.94	49.94	344.3	**49.95**	**344.4**	**3.058**	**21.08**	2.373	0.2075	995 to 2979
	1-3	1.156	29.37	0.2286	5.807	0.2643	170.5	12,414	55.22	12,415	55.22	46.97	323.8	**46.97**	**323.8**	**2.942**	**20.28**	2.209		
	1-4	1.158	29.40	0.2281	5.794	0.2641	170.4	12,524	55.71	12,538	55.77	47.43	327.0	**47.48**	**327.4**	**2.893**	**19.95**	2.243	0.1680	990 to 2998
	1-5	1.152	29.26	0.2303	5.850	0.2653	171.2	11,866	52.78	11,872	52.81	44.72	308.3	**44.74**	**308.5**	**2.876**	**19.83**	2.072		
	1-6	1.154	29.31	0.2312	5.872	0.2667	172.1	12,513	55.66	12,528	55.73	46.91	323.4	**46.97**	**323.8**	**2.830**	**19.51**	2.237		
	2-1	1.153	29.30	0.2327	5.911	0.2684	173.2	12,678	56.39	12,684	56.42	47.23	325.7	**47.25**	**325.8**	**2.808**	**19.36**	2.342		
	2-2	1.154	29.30	0.2370	6.020	0.2734	176.4	12,689	56.44	12,700	56.49	46.41	320.0	**46.45**	**320.3**	**2.829**	**19.50**	2.276	0.1756	1000 to 2994
	2-3	1.156	29.37	0.2378	6.039	0.2749	177.4	12,469	55.47	12,481	55.52	45.36	312.7	**45.40**	**313.0**	**2.748**	**18.95**	2.263		
	2-4	1.156	29.36	0.2385	6.057	0.2756	177.8	11,141	49.56	11,141	49.56	40.42	278.7	**40.42**	**278.7**	**2.732**	**18.84**	1.945	0.1808	994 to 2988
	2-5	1.153	29.28	0.2380	6.046	0.2744	177.0	12,294	54.69	12,306	54.74	44.80	308.9	**44.85**	**309.2**	**2.872**	**19.80**	2.125		
	2-6	1.156	29.37	0.2432	6.178	0.2812	181.4	12,788	56.88	12,808	56.97	45.47	313.5	**45.54**	**314.0**	**2.812**	**19.39**	2.223	0.1717	994 to 2991
	MEAN	***1.155***	***29.33***	***0.2338***	***5.939***	***0.2700***	***174.2***	***12,417***	***55.23***	***12,430***	***55.29***	***46.01***	***317.2***	***46.06***	***317.6***	***2.861***	***19.73***	***2.207***	***0.1807***	
	COV	***0.16***	***0.16***	***2.08***	***2.08***	***2.09***	***2.09***	***4.17***	***4.17***	***4.18***	***4.18***	***4.91***	***4.91***	***4.92***	***4.92***	***3.13***	***3.13***	***5.30***	***8.70***	

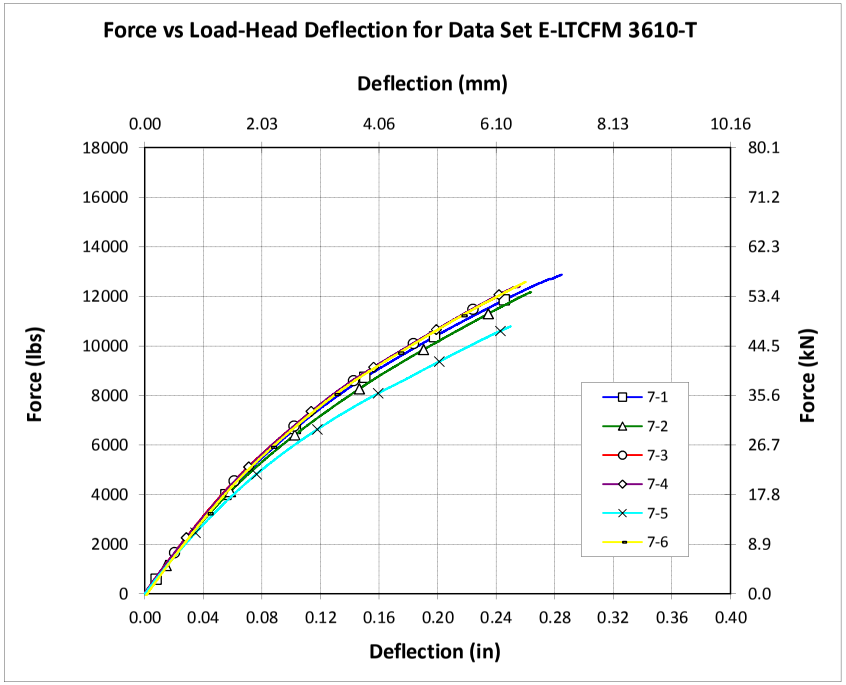




Tension Test Results Summary for the E-LTCFM 3610 Data Set (cont.)

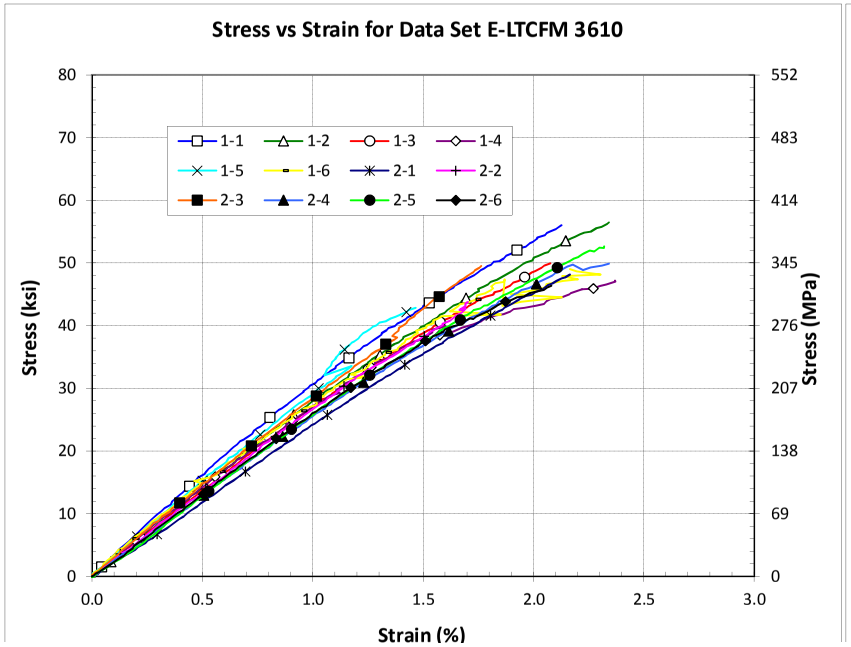
Notes	Specimen Number	Specimen Gage Area Dimensions						Failure Load				Strength				Modulus		Failure Strain	Poisson's Ratio	
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis			ν_{12}	Strain Range
	panel-spec.	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%		$x\,10^{-6}$
	7-1	1.163	29.53	0.2745	6.973	0.3192	205.9	12,887	57.32	12,879	57.29	40.37	278.3	**40.35**	**278.2**	**2.448**	**16.88**	2.315		
	7-2	1.161	29.50	0.2736	6.949	0.3177	205.0	12,162	54.10	12,171	54.14	38.28	263.9	**38.31**	**264.1**	**2.494**	**17.19**	2.088		
	7-3	1.168	29.65	0.2824	7.172	0.3296	212.7	12,096	53.81	12,107	53.86	36.69	253.0	**36.73**	**253.2**	**2.397**	**16.53**	2.102		
	7-4	1.167	29.63	0.2742	6.965	0.3199	206.4	12,404	55.17	12,404	55.17	38.78	267.4	**38.78**	**267.4**	**2.360**	**16.27**	2.256	0.1758	993 to 2984
	7-5	1.165	29.58	0.2833	7.196	0.3300	212.9	10,789	47.99	10,793	48.01	32.70	225.4	**32.71**	**225.5**	**2.467**	**17.01**	1.801		
	7-6	1.166	29.62	0.2772	7.041	0.3233	208.6	12,590	56.00	12,582	55.97	38.94	268.5	**38.92**	**268.3**	**2.592**	**17.87**	2.233		
Panel 7	***MEAN***	***1.165***	***29.59***	***0.2775***	***7.049***	***0.3233***	***208.6***	***12,155***	***54.07***	***12,156***	***54.07***	***37.63***	***259.4***	***37.63***	***259.5***	***2.460***	***16.96***	***2.132***	***0.1758***	
	COV	***0.21***	***0.21***	***1.55***	***1.55***	***1.66***	***1.66***	***6.00***	***6.00***	***5.96***	***5.96***	***7.15***	***7.15***	***7.12***	***7.12***	***3.28***	***3.28***	***8.69***	***NA***	
Panels 1, 2, & 7	***MEAN***	***1.158***	***29.42***	***0.2484***	***6.309***	***0.2878***	***185.7***	***12,330***	***54.85***	***12,338***	***54.88***	***43.22***	***298.0***	***43.25***	***298.2***	***2.727***	***18.80***	***2.182***	***0.1799***	
	COV	***0.45***	***0.45***	***8.73***	***8.73***	***9.17***	***9.17***	***4.77***	***4.77***	***4.77***	***4.77***	***10.8***	***10.8***	***10.9***	***10.9***	***7.78***	***7.78***	***6.52***	***7.90***	

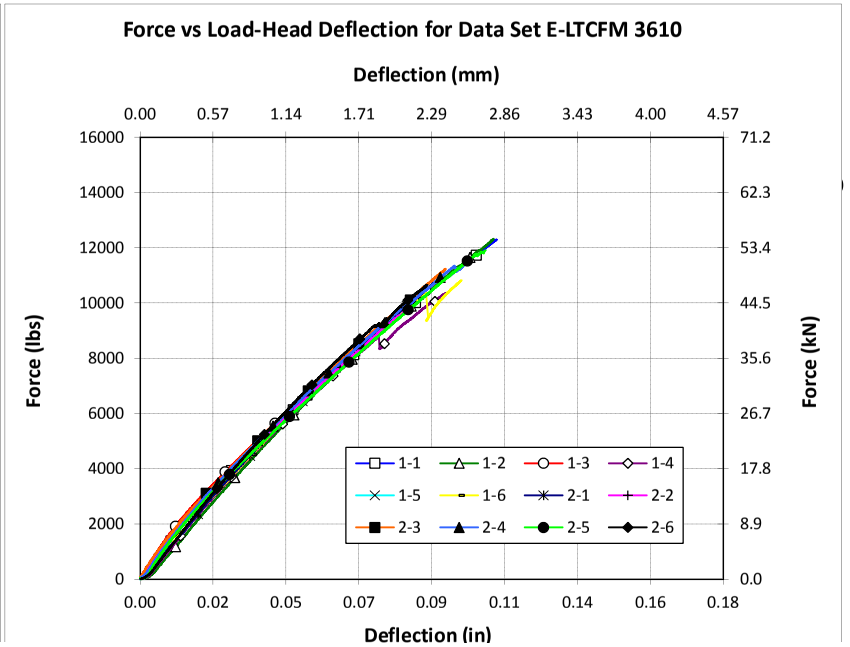




Compression Test Results Summary for the E-LTCFM 3610 Data Set

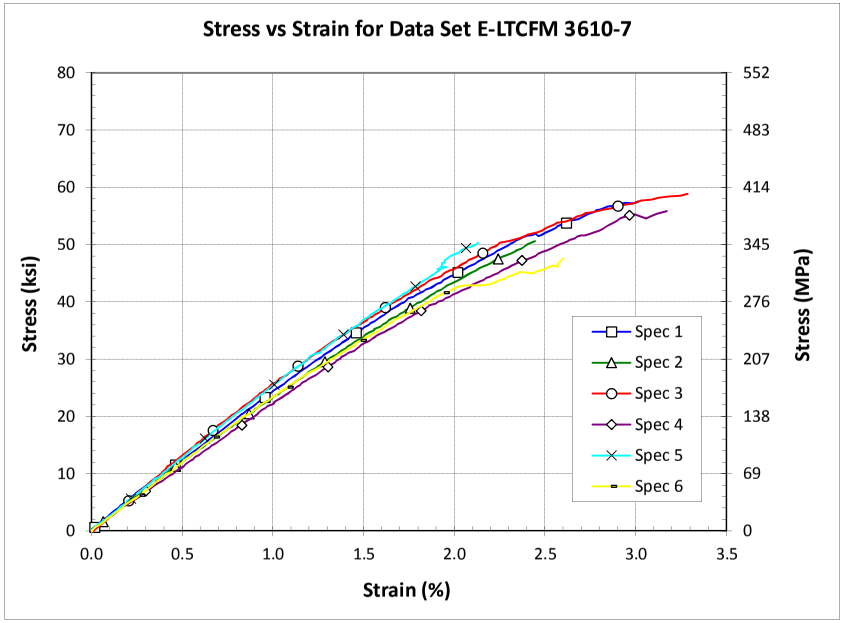
Notes	Specimen Number	Specimen Dimensions						Failure Load				Strength				Modulus		Failure		
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis		Strain	Local	Type
	#	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	Gage?	Code
	1-1	0.9534	24.22	0.2287	5.809	0.2180	140.7	12,217	54.34	12,297	54.70	56.03	386.3	**56.40**	**388.9**	**3.252**	**22.42**	2.128		
	1-2	0.9534	24.22	0.2273	5.774	0.2167	139.8	12,239	54.44	12,323	54.81	56.48	389.4	**56.86**	**392.1**	**2.893**	**19.95**	2.342		
	1-3	0.9509	24.15	0.2287	5.809	0.2175	140.3	10,854	48.28	10,903	48.50	49.92	344.2	**50.14**	**345.7**	**2.857**	**19.70**	2.077		
	1-4	0.9501	24.13	0.2293	5.825	0.2179	140.6	10,283	45.74	10,362	46.09	47.19	325.4	**47.55**	**327.9**	**2.915**	**20.10**	2.369		
	1-5	0.9513	24.16	0.2276	5.781	0.2165	139.7	9,272	41.25	9,341	41.55	42.83	295.3	**43.14**	**297.5**	**3.011**	**20.76**	1.467		
	1-6	0.9506	24.15	0.2301	5.845	0.2188	141.1	10,723	47.70	10,820	48.13	49.02	338.0	**49.46**	**341.0**	**3.002**	**20.70**	2.165		
	2-1	0.9526	24.20	0.2378	6.041	0.2266	146.2	10,909	48.53	10,969	48.79	48.15	332.0	**48.42**	**333.8**	**2.233**	**15.39**	2.166		
	2-2	0.9515	24.17	0.2339	5.941	0.2225	143.6	9,745	43.35	9,842	43.78	43.79	301.9	**44.23**	**304.9**	**2.766**	**19.07**	1.704		
	2-3	0.9529	24.20	0.2366	6.010	0.2255	145.5	11,173	49.70	11,243	50.01	49.55	341.7	**49.86**	**343.8**	**2.948**	**20.33**	1.764		
	2-4	0.9539	24.23	0.2379	6.044	0.2270	146.4	11,327	50.38	11,426	50.83	49.91	344.1	**50.34**	**347.1**	**2.544**	**17.54**	2.343		
	2-5	0.9514	24.16	0.2367	6.013	0.2252	145.3	11,854	52.73	11,911	52.98	52.64	362.9	**52.89**	**364.7**	**2.623**	**18.08**	2.320		
	2-6	0.9520	24.18	0.2406	6.111	0.2290	147.8	10,624	47.26	10,660	47.42	46.39	319.8	**46.54**	**320.9**	**2.762**	**19.04**	2.081		
	MEAN	***0.9520***	***24.18***	***0.2329***	***5.917***	***0.2218***	***143.1***	***10,935***	***48.64***	***11,008***	***48.97***	***49.32***	***340.1***	***49.65***	***342.4***	***2.817***	***19.42***	***2.077***		
	COV	***0.13***	***0.13***	***2.06***	***2.06***	***2.10***	***2.10***	***8.34***	***8.34***	***8.29***	***8.29***	***8.54***	***8.54***	***8.51***	***8.51***	***9.29***	***9.29***	***13.88***		

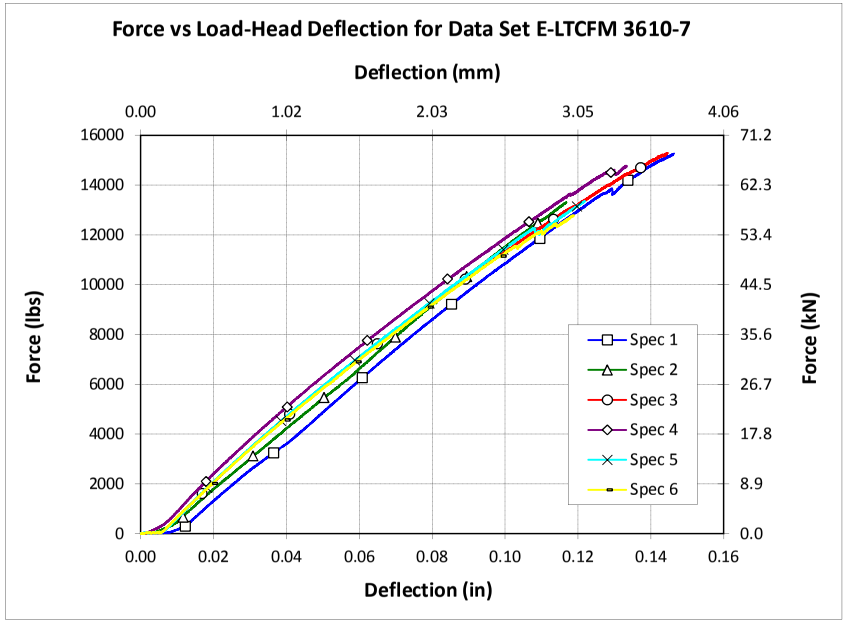




Compression Test Results Summary for the E-LTCFM 3610-7 Data Set

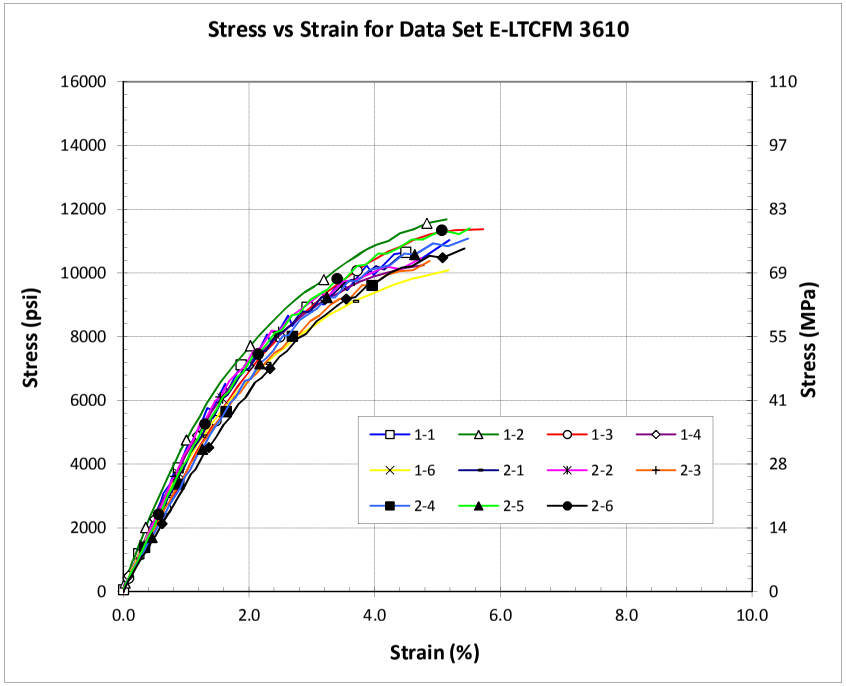
Notes	Specimen Number #	Specimen Dimensions: Width in	Width mm	Thickness in	Thickness mm	Area in²	Area mm²	Failure Load: Aramis lbs.	Aramis kN	Instron lbs.	Instron kN	Strength: Aramis ksi	Aramis MPa	Instron ksi	Instron MPa	Modulus: Aramis Msi	Aramis GPa	Failure: Strain %	Local Gage?	Type Code
	7-1	0.9643	24.49	0.2742	6.966	0.2644	170.6	15,213	67.67	15,264	67.90	57.53	396.7	**57.72**	**398.0**	**2.498**	**17.22**	3.011		
	7-2	0.9650	24.51	0.2699	6.855	0.2604	168.0	13,181	58.63	13,314	59.22	50.61	348.9	**51.12**	**352.4**	**2.322**	**16.01**	2.446		
	7-3	0.9718	24.68	0.2666	6.772	0.2591	167.1	15,257	67.87	15,294	68.03	58.89	406.1	**59.04**	**407.0**	**2.671**	**18.41**	3.287		
	7-4	0.9666	24.55	0.2723	6.917	0.2633	169.8	14,697	65.38	14,775	65.72	55.83	384.9	**56.12**	**387.0**	**2.236**	**15.42**	3.171		
	7-5	0.9684	24.60	0.2728	6.929	0.2642	170.4	13,291	59.12	13,351	59.39	50.31	346.9	**50.54**	**348.4**	**2.551**	**17.59**	2.131		
	7-6	0.9656	24.53	0.2768	7.031	0.2673	172.5	12,698	56.48	12,789	56.89	47.50	327.5	**47.84**	**329.9**	**2.326**	**16.04**	2.599		
Panel 7	***MEAN***	***0.9669***	***24.56***	***0.2721***	***6.912***	***0.2631***	***169.8***	***14,056***	***62.53***	***14,131***	***62.86***	***53.45***	***368.5***	***53.73***	***370.5***	***2.434***	***16.78***	***2.774***		
	COV	***0.29***	***0.29***	***1.30***	***1.30***	***1.13***	***1.13***	***8.04***	***8.04***	***7.84***	***7.84***	***8.58***	***8.58***	***8.39***	***8.39***	***6.80***	***6.80***	***16.36***		
Panel 1, 2, & 7 Combined	***MEAN***	***0.9570***	***24.31***	***0.2460***	***6.248***	***0.2355***	***152.0***	***11,975***	***53.27***	***12,049***	***53.60***	***50.7***	***349.6***	***51.01***	***351.7***	***2.689***	***18.54***	***2.309***		
	COV	***0.78***	***0.78***	***7.92***	***7.92***	***8.69***	***8.69***	***14.95***	***14.95***	***14.83***	***14.83***	***9.18***	***9.18***	***9.07***	***9.07***	***10.96***	***10.96***	***20.71***		

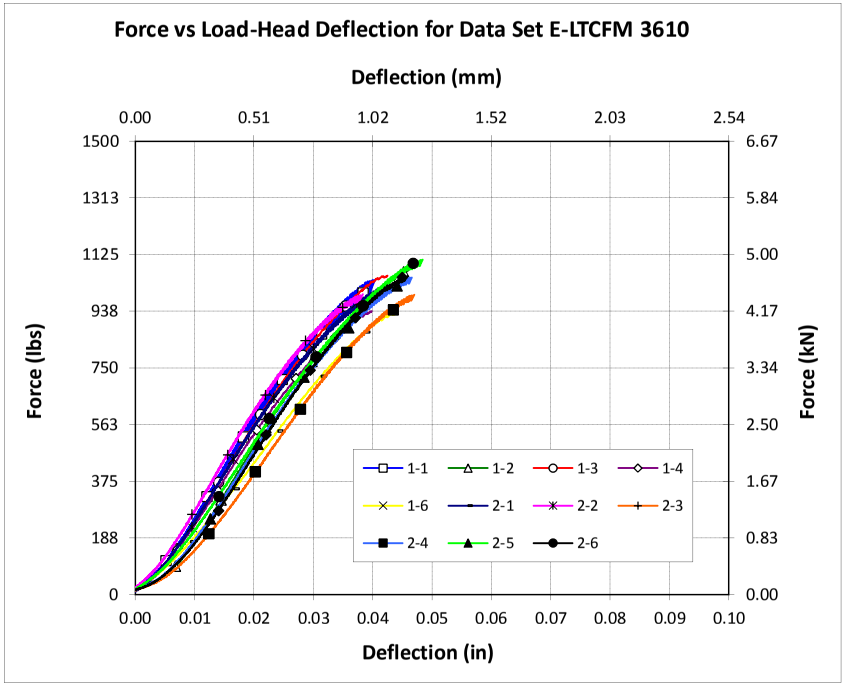




Shear Test Results Summary for the E-LTCFM 3610 Data Set

Notes	Specimen Number #	V-Notch Dimensions Width in	Width mm	Thickness in	Thickness mm	Area in^2	Area mm^2	Maximum Load Aramis lbs.	Aramis kN	Instron lbs.	Instron kN	Strength at Max Load Aramis ksi	Aramis MPa	Instron ksi	Instron MPa	Modulus Aramis ksi	Modulus Aramis Mpa	0.2% Offset Strain %	0.2% Offset Strength ksi	0.2% Offset Strength MPa
	1-1	0.4040	10.26	0.2331	5.919	0.0942	60.74	1,039	4.620	1,041	4.632	11.03	76.05	**11.06**	**76.25**	**0.4573**	**3.153**	1.620	6.500	44.82
	1-2	0.4015	10.20	0.2281	5.792	0.0916	59.07	1,069	4.756	1,071	4.766	11.68	80.52	**11.70**	**80.68**	**0.4891**	**3.373**	1.540	6.500	44.82
	1-3	0.4018	10.20	0.2305	5.855	0.0926	59.74	1,053	4.682	1,055	4.692	11.37	78.37	**11.39**	**78.53**	**0.3762**	**2.594**	2.100	7.125	49.13
	1-4	0.4008	10.18	0.2264	5.749	0.0907	58.52	930	4.135	938	4.172	10.25	70.66	**10.34**	**71.29**	**0.4449**	**3.068**	1.570	6.100	42.06
Operator Error	1-5	0.4038	10.26	0.2324	5.903	0.0938	60.54													
	1-6	0.4005	10.17	0.2287	5.810	0.0916	59.10	924	4.111	931	4.141	10.09	69.55	**10.16**	**70.07**	**0.4295**	**2.961**	1.450	5.400	37.23
	2-1	0.4030	10.24	0.2346	5.958	0.0945	60.98	994	4.421	1,015	4.514	10.51	72.50	**10.74**	**74.02**	**0.3857**	**2.659**	2.100	7.350	50.68
	2-2	0.3995	10.15	0.2357	5.986	0.0942	60.74	986	4.384	993	4.418	10.47	72.17	**10.55**	**72.74**	**0.4465**	**3.078**	1.680	6.610	45.58
	2-3	0.4020	10.21	0.2349	5.967	0.0944	60.93	980	4.359	992	4.412	10.38	71.55	**10.50**	**72.42**	**0.3719**	**2.564**	1.930	6.430	44.33
	2-4	0.4003	10.17	0.2342	5.948	0.0937	60.47	1,039	4.620	1,049	4.667	11.08	76.39	**11.19**	**77.17**	**0.3464**	**2.388**	2.390	7.565	52.16
	2-5	0.3985	10.12	0.2398	6.090	0.0956	61.65	1,089	4.843	1,108	4.930	11.40	78.57	**11.60**	**79.97**	**0.4254**	**2.933**	1.680	6.280	43.30
	2-6	0.4015	10.20	0.2416	6.136	0.0970	62.58	1,044	4.645	1,054	4.689	10.77	74.22	**10.87**	**74.93**	**0.3367**	**2.322**	2.190	6.720	46.33
	MEAN	***0.4014***	***10.20***	***0.2333***	***5.926***	***0.0937***	***60.42***	***1,013***	***4.507***	***1,023***	***4.548***	***10.82***	***74.60***	***10.92***	***75.28***	***0.4100***	***2.827***	***1.841***	***6.598***	***45.49***
	COV	***0.41***	***0.41***	***1.94***	***1.94***	***1.90***	***1.90***	***5.39***	***5.39***	***5.38***	***5.38***	***4.85***	***4.85***	***4.71***	***4.71***	***12.02***	***12.02***	***17.03***	***9.13***	***9.13***





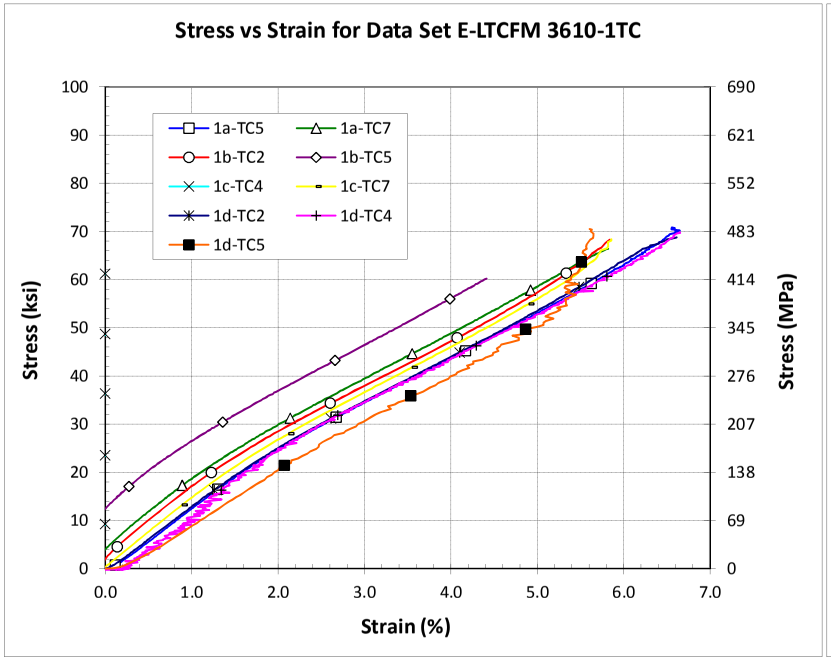
Through-Thickness Compression Test Results Summary for the E-LTCFM 3610-1 Data Set

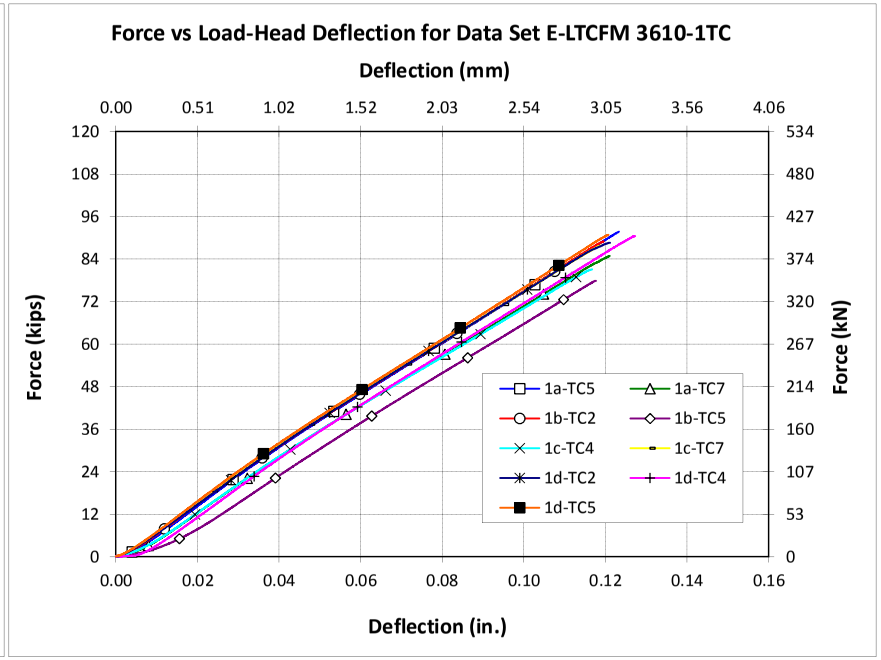
Notes	Specimen Number panel-spec.	Specimen Dimensions: Diameter in	Diameter mm	Thickness in	Thickness mm	Area in^2	Area mm^2	Failure Load: Aramis kips	Aramis kN	Instron kips	Instron kN	Strength: Aramis ksi	Aramis MPa	Instron ksi	Instron MPa	Modulus: Aramis Msi	Aramis GPa	Failure Strain %	Poisson's ν_{31}	Poisson's ν_{32}
2	1a-TC5	1.284	32.61	0.9242	23.47	1.295	835.3	91.72	408.0	91.73	408.0	70.85	488.5	**70.85**	**488.5**	**1.373**	**9.465**	6.559		
2, 3	1a-TC7	1.276	32.40	0.9248	23.49	1.278	824.7	84.82	377.3	84.87	377.5	66.36	457.5	**66.40**	**457.8**	**1.412**	**9.733**	5.824	0.2433	0.2725
1	1b-TC2	1.287	32.68	0.9362	23.78	1.300	838.6	88.81	395.0	89.01	395.9	68.32	471.1	**68.47**	**472.1**	**1.436**	**9.901**	5.839		
2, 3	1b-TC5	1.282	32.57	0.9358	23.77	1.291	833.0	77.76	345.9	77.90	346.5	60.23	415.2	**60.33**	**416.0**	**1.309**	**9.029**	4.417	0.2605	0.2465
2, 3	1c-TC4	1.278	32.47	0.9407	23.89	1.284	828.1	80.96	360.1	81.12	360.8	63.07	434.9	**63.19**	**435.7**				0.2281	0.2572
2	1c-TC7	1.278	32.47	0.9822	24.95	1.283	827.9	87.76	390.4	87.85	390.8	68.39	471.5	**68.45**	**472.0**	**1.438**	**9.914**	5.858		
1	1d-TC2	1.281	32.53	0.9272	23.55	1.288	831.2	88.64	394.3	88.64	394.3	68.81	474.4	**68.80**	**474.4**	**1.388**	**9.571**	6.615		
2	1d-TC4	1.282	32.56	0.9268	23.54	1.290	832.5	90.07	400.7	90.53	402.7	69.81	481.3	**70.16**	**483.7**	**1.437**	**9.908**	6.647		
2	1d-TC5	1.280	32.51	0.9295	23.61	1.287	830.3	90.73	403.6	90.83	404.0	70.50	486.1	**70.58**	**486.6**	**1.152**	**7.941**	5.606		
Panel 1	***MEAN***	***1.280***	***32.52***	***0.9350***	***23.75***	***1.288***	***830.8***	***86.81***	***386.2***	***86.94***	***386.7***	***67.37***	***464.5***	***67.47***	***465.2***	***1.368***	***9.433***	***5.920***	***0.2514***	
	COV (%)	***0.22***	***0.22***	***1.48***	***1.48***	***0.44***	***0.44***	***5.4***	***5.4***	***5.4***	***5.4***	***5.3***	***5.3***	***5.3***	***5.3***	***7.1***	***7.1***	***12.4***	***6.1***	
Panels 1 & 2	***MEAN***	***1.280***	***32.50***	***0.9612***	***24.41***	***1.286***	***829.7***	***83.97***	***373.5***	***84.08***	***374.0***	***65.18***	***449.4***	***65.26***	***450.0***	***1.368***	***9.431***	***5.744***	***0.2480***	
	COV (%)	***0.3***	***0.3***	***3.1***	***3.1***	***0.5***	***0.5***	***6.1***	***6.1***	***6.1***	***6.1***	***6.0***	***6.0***	***6.0***	***6.0***	***6.7***	***6.7***	***10.8***	***9.3***	

Note 1: Aramis pattern is in the 1-direction.

Note 2: Aramis pattern is in the 2-direction.

Note 3: Load mod





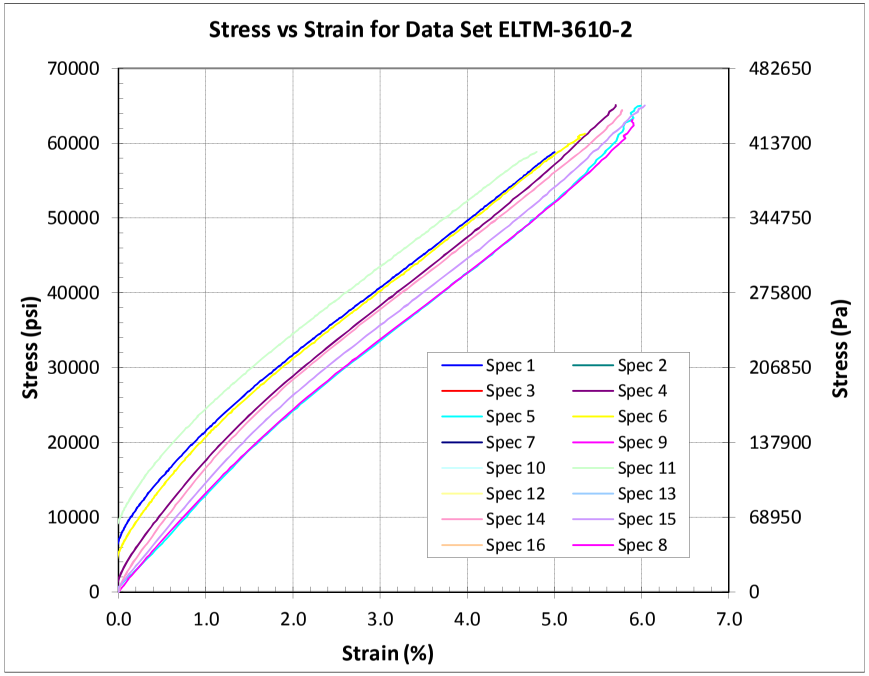
Through-Thickness Compression Test Results Summary for the ELTM-3610-2 Data Set

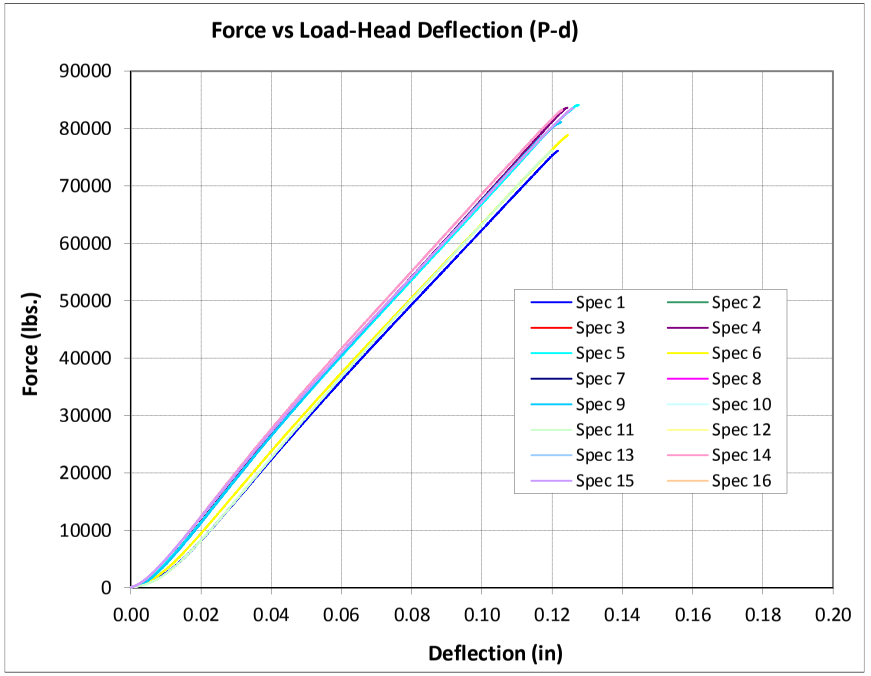
Notes	Specimen Number #	Specimen Dimensions: Diameter in	Diameter mm	Thickness in	Thickness mm	Area in²	Area mm²	Failure Load: Aramis kips	Aramis kN	Instron kips	Instron kN	Strength: Aramis ksi	Aramis MPa	Instron ksi	Instron MPa	Modulus: Aramis Msi	Aramis GPa	Failure Strain %	Poisson's ν_{31}	Poisson's ν_{32}
1, 3	1a-TC2	1.282	32.57	0.9925	25.21	1.292	833.3	75.97	337.9	76.10	338.5	58.82	405.5	**58.92**	**406.2**	**1.300**	**8.96**	5.002	0.2823	0.2048
1	1a-TC7	1.279	32.48	0.9913	25.18	1.285	828.8	83.64	372.0	83.61	371.9	65.11	448.9	**65.09**	**448.8**	**1.452**	**10.013**	5.702		
2	1b-TC2	1.284	32.61	0.9902	25.15	1.294	835.0	84.14	374.3	84.15	374.3	65.01	448.2	**65.02**	**448.3**	**1.273**	**8.774**	5.987		
1, 3	1b-TC4	1.279	32.48	0.9890	25.12	1.284	828.5	78.70	350.1	78.88	350.9	61.29	422.6	**61.43**	**423.5**	**1.433**	**9.880**	5.351	0.2187	0.2265
1	1c-TC2	1.278	32.47	0.9820	24.94	1.283	828.0	81.00	360.3	81.14	360.9	63.11	435.1	**63.22**	**435.9**	**1.282**	**8.842**	5.896		
1, 3	1c-TC5	1.283	32.58	0.9847	25.01	1.292	833.8	76.07	338.4	76.18	338.9	58.86	405.8	**58.95**	**406.4**	**1.293**	**8.915**	4.797	0.2549	0.1990
1	1d-TC4	1.282	32.56	0.9925	25.21	1.291	832.8	83.15	369.8	83.28	370.5	64.41	444.1	**64.52**	**444.9**	**1.509**	**10.405**	5.776		
2	1d-TC5	1.279	32.48	0.9972	25.33	1.284	828.4	83.53	371.6	83.52	371.5	65.06	448.6	**65.05**	**448.5**	**1.399**	**9.649**	6.037		
	MEAN	***1.279***	***32.48***	***0.9874***	***25.08***	***1.284***	***828.7***	***80.77***	***359.3***	***80.86***	***359.7***	***62.71***	***432.4***	***62.77***	***432.8***	***1.368***	***9.430***	***5.568***	***0.2310***	
	COV	***0.3***	***0.3***	***1.3***	***1.3***	***0.6***	***0.6***	***4.2***	***4.2***	***4.2***	***4.2***	***4.3***	***4.3***	***4.3***	***4.3***	***6.7***	***6.7***	***8.4***	***13.8***	

Note 1: Aramis pattern is in the 1-direction.

Note 2: Aramis pattern is in the 2-direction.

Note 3: Load mod





Mode-I Fracture Test Summary for the E-LTCFM 3610/Epovia Vinyl Ester Test Specimens

x-diff *mm*
0.035

Δ Slope *%*
5.00%

Specimen		Nonlinear Onset: Position Change			Nonlinear Onset: Slope Change			Linear Region		Peak Load		Individual Panel Stats		
	ID	x-diff	Position	Load	Δ Slope	Position	Load	Load Range	Stiffness			Load-slp	Stiffness	*Peak Load*
#	*panel #-sp #*	*mm*	*mm*	*N*	*%*	*mm*	*N*	*N*	*N/mm*	*N*	*lbf*	*mean (COV)*	*mean (COV)*	*mean (COV)*
Spec 1	E-m1-1 5-2	0.035	3.098	52.89	5.00	2.799	49.06	14-28	16.21	90.97	20.47			
Spec 2	E-m1-2 5-17	0.035	3.287	50.72	5.00	3.079	48.46	14-28	14.74	76.68	17.25			
Spec 3	E-m1-3 5a-10	0.035	3.459	50.82	5.00	3.289	49.97	14-28	14.29	79.30	17.84	49.2 (1.5%)	15.1 (6.7%)	82.3 (9.2%)
Spec 4	E-m1-4 6-8	0.035	2.994	46.36	5.00	2.870	45.10	14-28	14.47	65.09	14.64			
Spec 5	E-m1-5 6a-1	0.035	3.482	52.64	5.00	3.362	53.09	14-28	14.52	80.31	18.07			
Spec 6	E-m1-6 6a-16	0.035	3.431	47.30	5.00	3.268	46.32	14-28	13.37	70.33	15.82	48.2 (8.9%)	14.1 (4.6%)	71.9 (10.7%)
Spec 7	E-m1-7 3-11	0.035	3.282	33.62	5.00	3.174	32.64	14-28	9.867	69.41	15.62			
Spec 8	E-m1-8 3a-6	0.035	4.728	50.37	5.00	4.162	45.52	14-28	10.52	63.51	14.29			
Spec 9	E-m1-9 3a-19	0.035	4.821	52.13	5.00	4.573	49.70	24-38	11.32	66.77	15.02	42.6 (20.9%)	10.6 (6.9%)	66.6 (4.4%)
Spec 10	E-m1-10 4-2	0.035	3.949	57.32	5.00	3.396	50.97	14-28	13.84	85.71	19.28			
Spec 11	E-m1-11 4-16	0.035	3.187	45.73	5.00	2.920	42.84	14-28	13.81	78.10	17.57			
Spec 12	E-m1-12 4a-9	0.035	3.411	48.94	5.00	3.183	46.22	14-28	14.28	83.28	18.74	46.7 (8.7%)	14 (1.9%)	82.4 (4.7%)
	Max		4.821	57.32		4.573	53.09	**x-diff Range**	16.21	90.97	20.47			
	Min		2.994	33.62		2.799	32.64	28.5%	9.867	63.51	14.29			
	Mean		**3.594**	**49.07**		**3.339**	**46.66**	**Slope Range**	**13.44**	**75.79**	**17.05**			
	COV		**16.7%**	**11.9%**		**15.7%**	**11.3%**	30.0%	**14.0%**	**11.5%**	**11.5%**			
						Range Start %		30.0%						

Propagation Start *(mm)*	60

Panel ID	Toughness Calculations: Position	Load	ao	a	Δ	b	Toughness (G1): Onset	Prop
panel # - sp #	*mm*	*N*	*mm*		*mm*	*mm*	*J/m²*	*J/m²*
E-m1-1 5-2	2.799	49.06	50.96	47.34	4.024	26.02	154.1	699.6
E-m1-2 5-17	3.079	48.46	50.81	49.18	4.165	26.06	161.0	645.9
E-m1-3 5a-10	3.289	49.97	51.12	49.80	4.229	26.20	174.2	622.2
E-m1-4 6-8	2.870	45.10	50.30	49.21	3.929	25.91	141.0	484.3
E-m1-5 6a-1	3.362	53.09	49.52	49.12	4.272	25.66	195.4	876.6
E-m1-6 6a-16	3.268	46.32	49.98	51.03	4.399	26.01	157.5	650.7
E-m1-7 3-11	3.174	32.64	51.44	51.02	4.081	25.97	108.6	773.1
E-m1-8 3a-6	4.162	45.52	50.65	49.92	4.042	25.96	202.8	781.7
E-m1-9 3a-19	4.573	49.70	50.38	50.03	4.120	26.17	240.5	693.0
E-m1-10 4-2	3.396	50.97	51.16	50.01	4.384	26.21	182.1	890.6
E-m1-11 4-16	2.920	42.84	51.15	50.41	4.299	26.34	130.2	852.5
E-m1-12 4a-9	3.183	46.22	50.76	50.60	4.255	26.25	153.2	644.7
Max	4.573	53.09	51.44	51.03	4.399	26.34	240.5	890.6
Min	2.799	32.64	49.52	47.34	3.929	25.66	108.6	484.3
Mean	**3.339**	**46.66**	**50.69**	**49.81**	**4.183**	**26.07**	**166.7**	**717.9**
COV	**15.7%**	**11.3%**	**1.1%**	**2.0%**	**3.5%**	**0.7%**	**21.2%**	**16.8%**

Compliance Calibration Results

Panels 4-6 Compliance

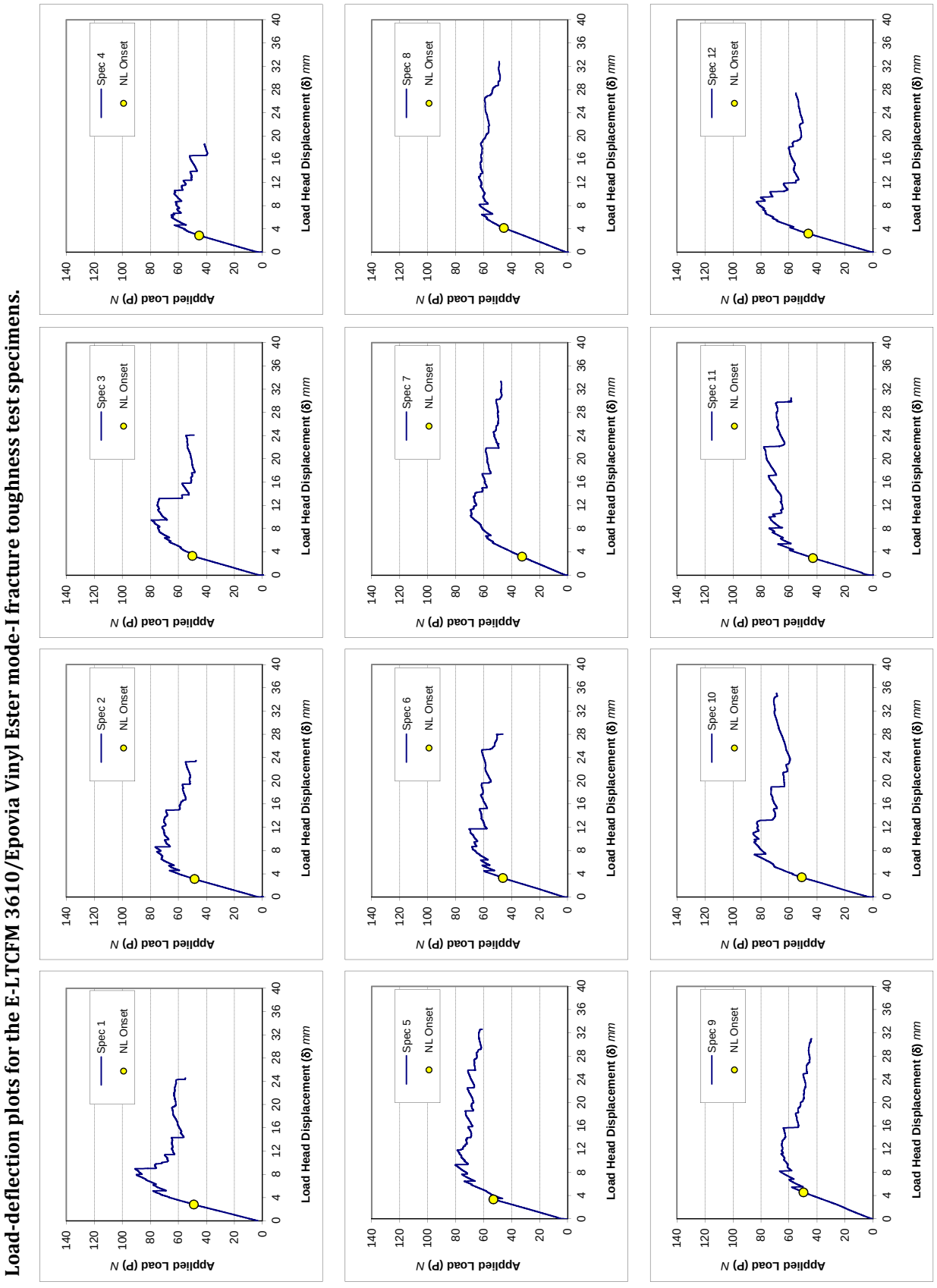
	US	SI
m	1.712E-03	1.023E-06
x	2.8332	2.8332
R^2	0.9939	

$$C = m \cdot a^x$$

Panel 3 Compliance

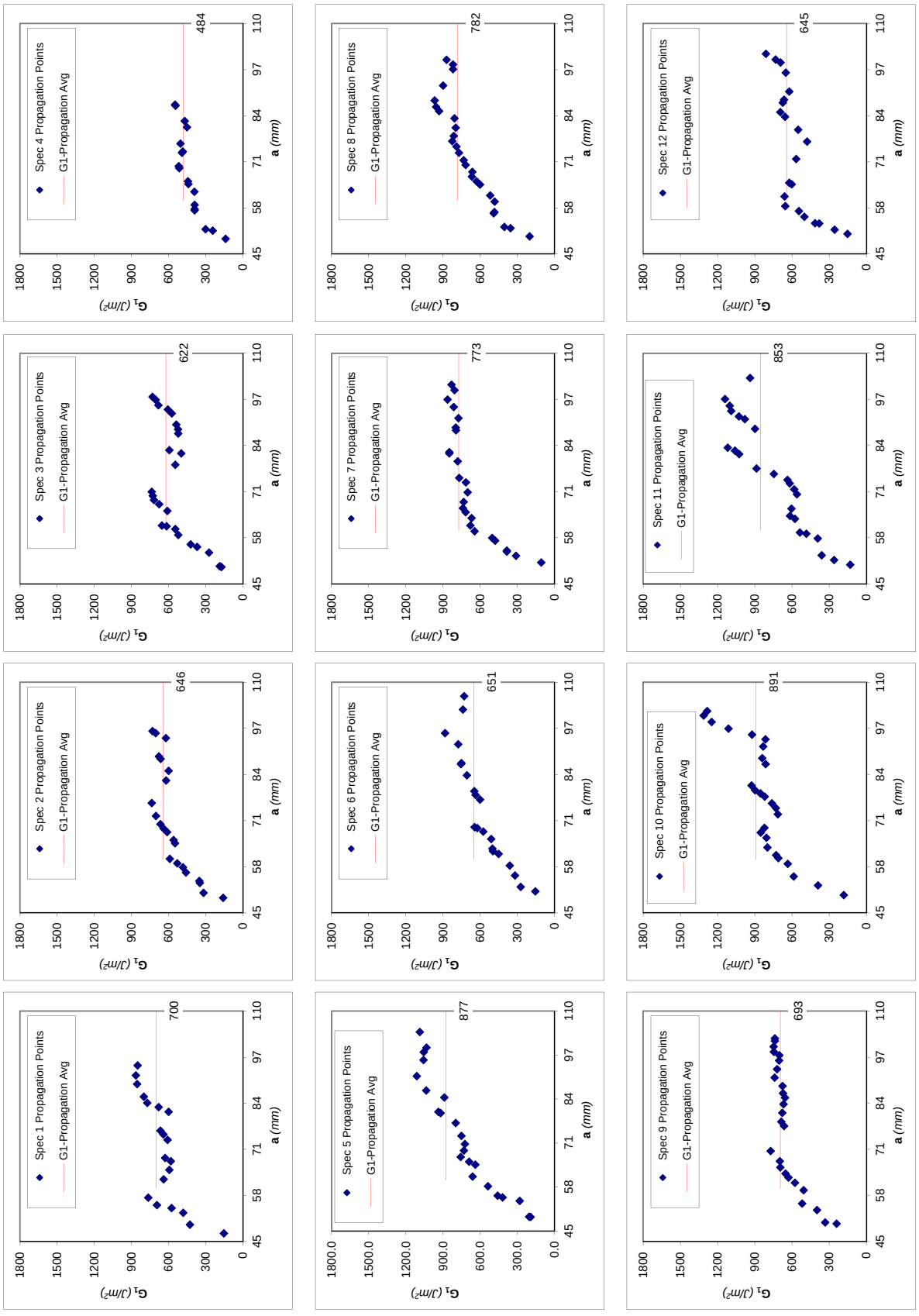
	US	SI
m	2.348E-03	1.367E-06
x	2.8414	2.8414
R^2	0.9982	

$$a = \sqrt[x]{\frac{C}{m}}$$



Load-deflection plots for the E-LTCFM 3610/Epovia Vinyl Ester mode-I fracture toughness test specimens.

Resistance curves (R-curves) for the E-LTCFM 3610/Epovia Vinyl Ester mode-I fracture toughness test specimens.



Mode-II Fracture Toughness Test Summary for the E-LTCFM 3610/Epovia Vinyl Ester Test Specimens

Specimen Dimensions

Specimen ID	SI Units (SI) Width mean	Width CV	Thickness mean	Thickness CV	English Units (US) Width mean	Width CV	Thickness mean	Thickness CV	Initial Crack (a_o) (SI)	(US)
panel # - spec. #	*mm*	*%*	*mm*	*%*	*in*	*%*	*in*	*%*	*mm*	*in*
E-m2-1 5-10	26.07	0.2	7.271	2.2	1.026	0.2	0.2862	2.2	25.4	1.00
E-m2-2 5a-5	26.04	0.1	7.111	1.7	1.025	0.1	0.2799	1.7	25.4	1.00
E-m2-3 5a-18	25.92	0.2	7.002	2.2	1.021	0.2	0.2757	2.2	25.4	1.00
E-m2-4 6-6	25.87	0.1	6.828	2.4	1.019	0.1	0.2688	2.4	25.4	1.00
E-m2-5 6-16	25.99	0.2	7.002	2.2	1.023	0.2	0.2757	2.2	25.4	1.00
E-m2-6 6a-9	25.95	0.1	6.905	0.8	1.022	0.1	0.2718	0.8	25.4	1.00
E-m2-7 3-6	25.85	0.1	5.974	0.8	1.018	0.1	0.2352	0.8	25.4	1.00
E-m2-8 3-19	26.04	0.1	5.928	2.4	1.025	0.1	0.2334	2.4	25.4	1.00
E-m2-9 3a-14	26.10	0.1	5.940	2.1	1.028	0.1	0.2339	2.1	25.4	1.00
E-m2-10 4-9	26.26	0.5	7.086	1.0	1.034	0.5	0.2790	1.0	25.4	1.00
E-m2-11 4a-4	26.13	0.2	6.924	0.8	1.029	0.2	0.2726	0.8	25.4	1.00
E-m2-12 4a-17	26.41	0.3	7.063	2.0	1.040	0.3	0.2781	2.0	25.4	1.00
Mean	**26.05**	**0.6**	**6.753**	**7.4**	**1.026**	**0.6**	**0.2659**	**7.4**	**25.4**	**1.00**

Proposed ASTM Standard

$$C = A + ma^3 \qquad G_Q = \frac{3mP_{Max}^2 a_o^2}{2B}$$

$$\%G_Q = Max\left[\frac{100\left(P_j a_j\right)^2}{\left(P_{Max} a_o\right)^2}\right];\ j = 1,2$$

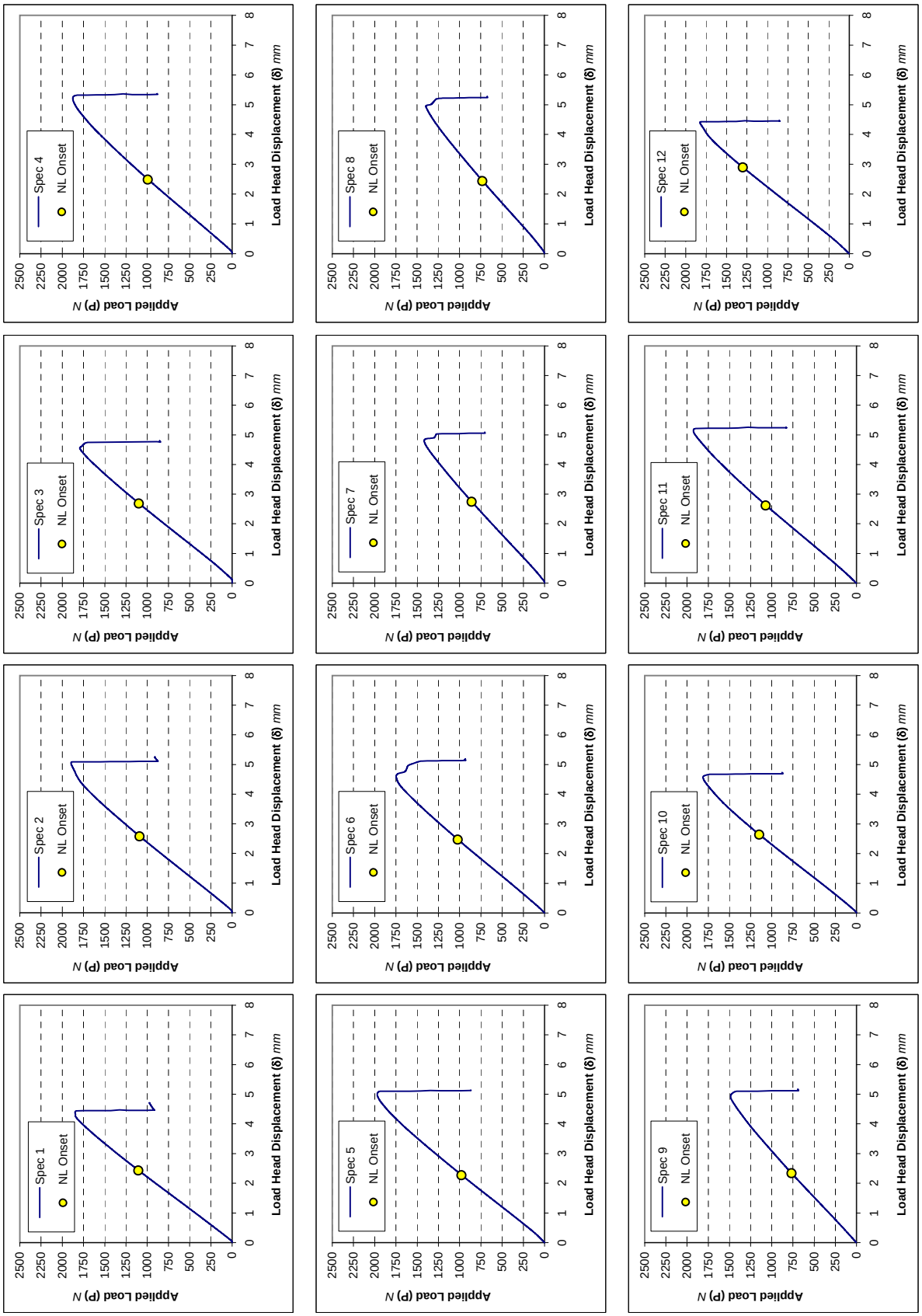
European Standard

$$G_{IIC} = \frac{9 \times P \times a^2 \times d \times 1000}{2 \times w(1/4L^3 + 3a^3)}$$

Toughness Calculations

Specimen #	Specimen ID	NL-Onset Load	Max Load (N) a_o	Max Load (N) ao - 8.5	Max Load (N) ao + 8.5	Compliance (mm/N) a_o	Compliance (mm/N) ao - 8.5	Compliance (mm/N) ao + 8.5	%G_Q (%) a_o	%G_Q (%) ao - 8.5	%G_Q (%) ao + 8.5	ASTM Standard: Compliance Cal. m	R^2	Toughness G_{II} NL	Panel Stats Mean (CV)	European Standard G_{II} NL
#	*ID*	*N*	a_o	ao - 8.5	ao + 8.5	a_o	ao - 8.5	ao + 8.5	a_o	ao - 8.5	ao + 8.5	*1/Nmm²*		*J/m²*	*J/m² (%)*	*J/m²*
Spec 1	**E-m2-1 5-10**	1104	1850	274.2	272.7	2.168E-03	2.000E-03	2.761E-03	100	2.74	10.8	2.294E-08	0.9834	1038		604.6
Spec 2	**E-m2-2 5a-5**	1089	1896	318.0	315.3	2.280E-03	2.071E-03	2.800E-03	100	3.78	14.9	2.167E-08	0.9966	954.4	988 (4.5)	630.0
Spec 3	**E-m2-3 5a-18**	1098	1792	404.9	414.6	2.295E-03	2.122E-03	2.841E-03	100	6.04	25.3	2.158E-08	0.9883	971.5		649.1
Spec 4	**E-m2-4 6-6**	991.3	1875	417.1	339.1	2.432E-03	2.153E-03	2.926E-03	100	7.86	20.8	2.264E-08	0.9994	832.3		560.9
Spec 5	**E-m2-5 6-16**	978.3	1970	444.1	343.2	2.264E-03	2.029E-03	2.815E-03	100	9.13	21.8	2.330E-08	0.9980	830.2	848 (3.5)	511.0
Spec 6	**E-m2-6 6a-9**	1021	1748	341.1	337.8	2.405E-03	2.217E-03	2.973E-03	100	4.97	19.5	2.268E-08	0.9902	882.4		579.4
Spec 7	**E-m2-7 3-6**	858.0	1419	340.9	336.5	3.064E-03	2.811E-03	3.845E-03	100	7.01	27.3	3.102E-08	0.9894	854.9		535.5
Spec 8	**E-m2-8 3-19**	730.1	1397	338.3	337.7	3.188E-03	2.875E-03	4.053E-03	100	9.54	38.0	3.518E-08	0.9935	697.1	765 (10.6)	403.2
Spec 9	**E-m2-9 3a-14**	766.9	1483	652.3	336.1	3.036E-03	2.731E-03	3.871E-03	100	32.2	34.2	3.404E-08	0.9939	742.2		410.7
Spec 10	**E-m2-10 4-9**	1148	1812	362.4	338.4	2.254E-03	2.016E-03	2.697E-03	100	4.43	15.5	2.000E-08	0.9998	972.2		685.7
Spec 11	**E-m2-11 4a-4**	1070	1921	341.0	336.4	2.434E-03	2.189E-03	3.020E-03	100	4.52	17.6	2.468E-08	0.9976	1047	1226 (30.7)	642.8
Spec 12	**E-m2-12 4a-17**	1300	1822	367.1	410.8	2.183E-03	1.954E-03	2.848E-03	100	3.54	17.8	2.675E-08	0.9916	1657		849.6
	Mean	**1013**	**1749**	**383.4**	**343.2**	**2.50E-03**	**2.26E-03**	**3.12E-03**	**100.0**	**7.98**	**22.0**	**2.55E-08**	**0.9935**	**956.6**		**588.5**
	COV	**16.1%**	**11.5%**	**25.1%**	**11.0%**	**14.8%**	**14.9%**	**15.8%**	**0.0%**	**99.6%**	**36.6%**	**20.0%**	**0.5%**	**25.7%**		**20.6%**

Load-deflection plots for the E-LTCFM 3610/Epovia Vinyl Ester mode-II fracture toughness test specimens

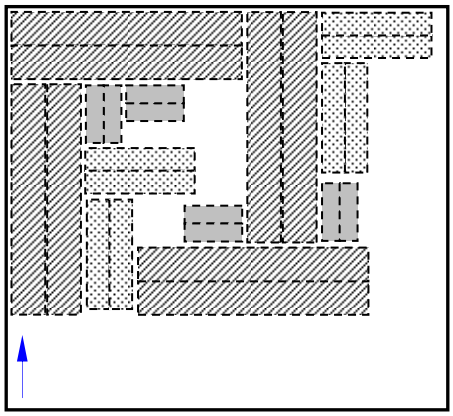


C-LA 1812 - Uniaxial (0°) *(94 / 0 / 0 / 0 / 6)*

In-Plane Properties

23” x 21” area (25” x 23” panel)

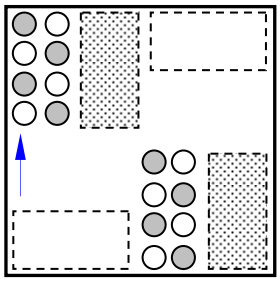
4 specimens/panel – 3 panels required



Through Thickness Properties

14” x 14” area (16” x 16” panel)

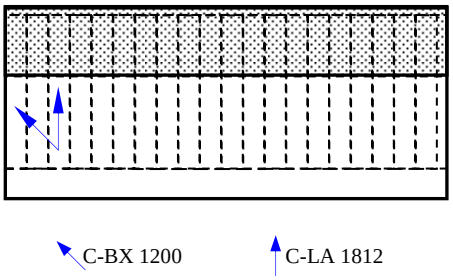
4 specimens/panel – 3 panels required



Fracture Properties

48” x 10” area (50” x 12” panel)

40 specimens/panel – 4 panels required



Thick ness	**0.10**	**1.00**	**0.182**
# of Layers	**4**	**40**	**3/45, 6/0**
50” Roll feet	**12**	**54**	**24**

Test	**Property**
Tension in 1-dir	E_{1t}, F_{1t}, v_{12}
Tension in 2-dir	E_{2t}, F_{2t}, v_{21}
Comp. in 1 dir	E_{1c}, F_{1c}, v_{12}
Comp. in 2-dir	E_{2c}, F_{2c}, v_{21}
Shear in 12-dir	G_{12}, F_{12}

Test	**Property**
Tension in 3-dir	E_{3t}, F_{3t}, $v_{31,}$, v_{32}
Comp. in 3-dir	E_{3c}, F_{3c}, $v_{31,}$, v_{32}
Shear in 13-dir	G_{13}, F_{13}
Shear in 23-dir	G_{23}, F_{23}

F_{13} & F_{23} are larger than what would be obtained from tests in the 31 and 32 directions

Test	**Property**
Mode-I	$G_{1c\ onset}$, $G_{1c\ propagation}$
Mode-II	$G_{2c\ onset}$, $G_{2c\ propagation}$

This is a mixed laminate with a C-BX 1200/C-LA 1812 interface.

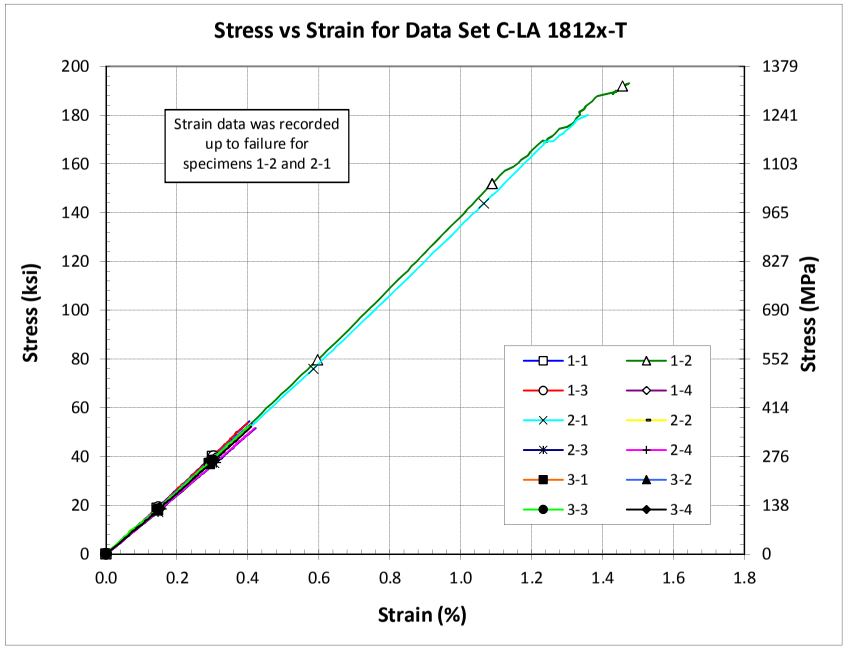
Tension Test Results Summary for the C-LA 1812x Data Set

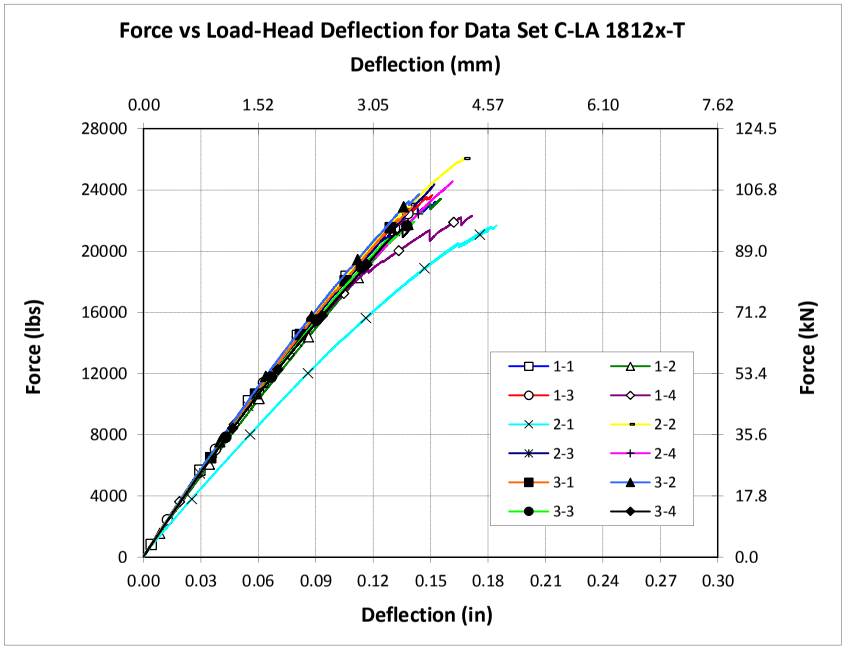
Notes	Specimen Number panel-spec.	Specimen Gage Area Dimensions: Width in	Width mm	Thickness in	Thickness mm	Area in²	Area mm²	Failure Load: Aramis [3] lbs.	Aramis [3] kN	Instron lbs.	Instron kN	Strength: Aramis [3] ksi	Aramis [3] MPa	Instron ksi	Instron MPa	Modulus: Aramis Msi	Aramis GPa	Failure Strain [2] %	Poisson's Ratio ν_{12}	Strain Range x 10⁻⁶
	1-1	0.9516	24.17	0.1183	3.004	0.1125	72.60	6,130	27.27	23,230	103.3	54.48	375.6	**206.4**	**1423**	**13.52**	**93.23**	0.404	0.4163	997 to 2997
	1-2	0.9531	24.21	0.1212	3.078	0.1155	74.53	22,302	99.21	23,427	104.2	193.1	1331	**202.8**	**1398**	**13.43**	**92.60**	1.475		
	1-3	0.9521	24.18	0.1184	3.008	0.1128	72.75	6,086	27.07	23,667	105.3	53.98	372.1	**209.9**	**1447**	**13.47**	**92.89**	0.400	0.3027	990 to 2994
	1-4	0.9515	24.17	0.1199	3.044	0.1140	73.57	6,119	27.22	22,307	99.23	53.66	370.0	**195.6**	**1349**	**12.95**	**89.27**	0.412		
1	2-1	0.9525	24.19	0.1261	3.202	0.1201	77.47	21,610	96.13	21,681	96.44	180.0	1241	**180.6**	**1245**	**12.74**	**87.87**	1.358		
	2-2	0.9529	24.20	0.1268	3.221	0.1208	77.95	6,130	27.27	26,057	115.9	50.74	349.8	**215.7**	**1487**	**12.56**	**86.60**	0.395	0.3105	987 to 2997
	2-3	0.9540	24.23	0.1243	3.156	0.1186	76.48	6,119	27.22	24,350	108.3	51.62	355.9	**205.4**	**1416**	**12.19**	**84.04**	0.422		
	2-4	0.9520	24.18	0.1238	3.145	0.1179	76.05	6,086	27.07	24,559	109.2	51.64	356.0	**208.3**	**1437**	**12.21**	**84.19**	0.420	0.4053	1000 to 2992
	3-1	0.9533	24.21	0.1233	3.131	0.1175	75.80	6,064	26.98	22,928	102.0	51.62	355.9	**195.2**	**1346**	**12.97**	**89.43**	0.399		
	3-2	0.9548	24.25	0.1222	3.104	0.1167	75.28	6,086	27.07	23,729	105.6	52.16	359.6	**203.4**	**1402**	**13.18**	**90.85**	0.399		
	3-3	0.9565	24.30	0.1207	3.065	0.1154	74.45	6,119	27.22	21,935	97.57	53.03	365.6	**190.1**	**1311**	**13.21**	**91.05**	0.409	0.4020	996 to 2989
	3-4	0.9525	24.19	0.1217	3.090	0.1159	74.76	6,053	26.93	21,552	95.87	52.24	360.2	**186.0**	**1282**	**12.89**	**88.89**	0.410		
	MEAN	***0.9531***	***24.21***	***0.1222***	***3.104***	***0.1165***	***75.14***	***8,742***	***38.89***	***23,285***	***103.6***	***74.85***	***516.1***	***199.9***	***1379***	***12.94***	***89.24***	***0.575***	***0.3551***	
	COV	***0.15***	***0.15***	***2.25***	***2.25***	***2.27***	***2.27***	***70.6***	***70.6***	***5.69***	***5.69***	***69.8***	***69.8***	***5.26***	***5.26***	***3.51***	***3.51***	***68.5***	***15.8***	

Note 1: The 22kip load-frame was used for specimen 2-1 and did not properly enclose the grip section of the specimen resulting in gripping issues. 100Kip load frame, which has a larger gripping area, was used for remaining specimens.

Note 2: Strain was NOT recorded up to failure on most specimens, but it was recorded over the strain range of 1000-3000 micro-strain to obtain modulus and Poisson's ratio.

Note 3: The Aramis Load and Strength values indicate the value up to which the strain was recorded. (Strain was recorded up to failure for specimens 1-2 and 2-1 only.)

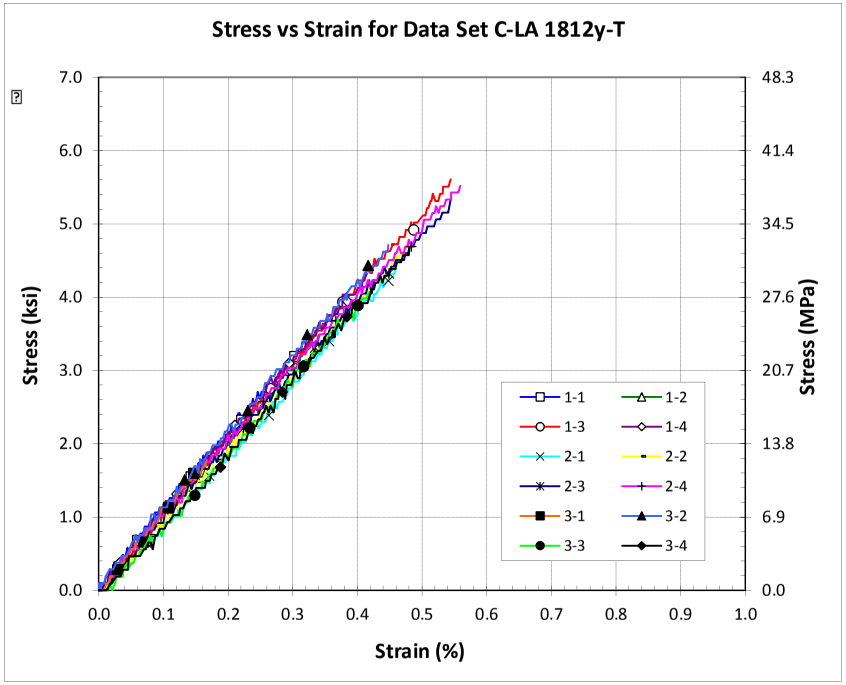


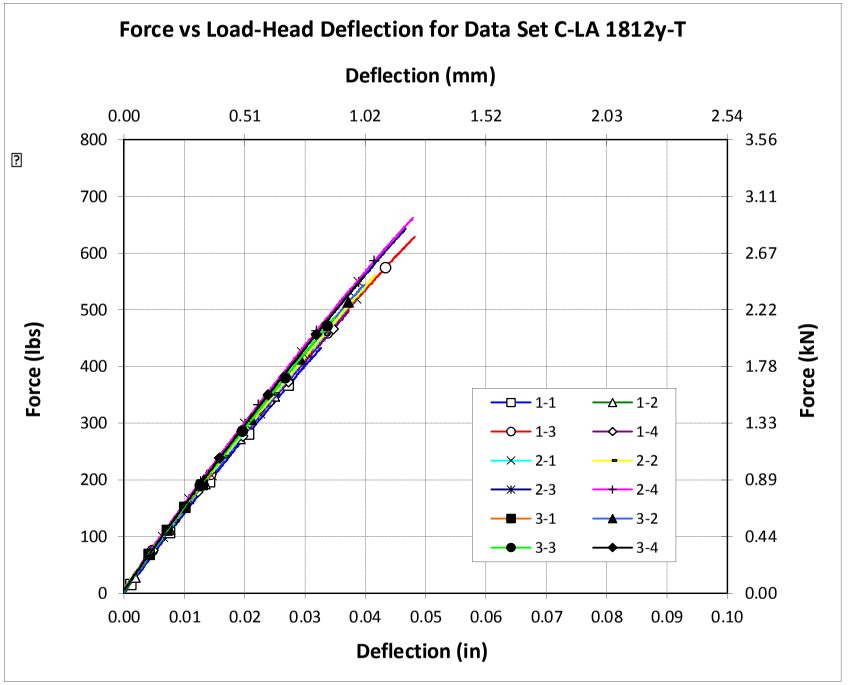


Tension Test Results Summary for the C-LA 1812y Data Set

Notes	Specimen Number	Specimen Gage Area Dimensions						Failure Load				Strength				Modulus		Failure Strain	
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis		Aramis	Strain Gage
	panel-spec.	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	%
	1-1	0.9536	24.22	0.1192	3.027	0.1136	73.32	439.5	1.955	432.4	1.923	3.867	26.66	**3.805**	**26.24**	**0.962**	**6.635**	0.3721	0.4139
	1-2	0.9528	24.20	0.1192	3.028	0.1136	73.28	395.5	1.759	397.4	1.768	3.482	24.01	**3.498**	**24.12**	**1.007**	**6.942**	0.3401	
	1-3	0.9543	24.24	0.1171	2.973	0.1117	72.06	626.2	2.786	629.2	2.799	5.607	38.66	**5.634**	**38.84**	**1.040**	**7.171**	0.5447	0.5374
	1-4	0.9583	24.34	0.1221	3.102	0.1170	75.51	505.4	2.248	498.7	2.218	4.318	29.77	**4.261**	**29.38**	**1.024**	**7.057**	0.4147	
	2-1	0.9556	24.27	0.1252	3.180	0.1196	77.18	527.3	2.346	539.0	2.397	4.408	30.39	**4.505**	**31.06**	**0.973**	**6.709**	0.4606	
	2-2	0.9514	24.16	0.1237	3.142	0.1177	75.92	549.3	2.443	561.6	2.498	4.668	32.19	**4.772**	**32.90**	**1.037**	**7.149**	0.4754	0.4691
	2-3	0.9554	24.27	0.1250	3.175	0.1194	77.06	637.2	2.834	643.8	2.864	5.335	36.78	**5.390**	**37.16**	**0.933**	**6.434**	0.5445	
	2-4	0.9585	24.35	0.1246	3.166	0.1195	77.07	659.2	2.932	662.3	2.946	5.518	38.04	**5.544**	**38.22**	**0.971**	**6.696**	0.5595	0.5669
1	3-1	0.9650	24.51	0.1212	3.079	0.1170	75.47	208.7	0.929	211.0	0.939	1.784	12.30	**1.804**	**12.44**			0.1675	
	3-2	0.9628	24.45	0.1211	3.075	0.1165	75.19	549.3	2.443	543.8	2.419	4.714	32.50	**4.666**	**32.17**	**1.034**	**7.130**	0.4479	
	3-3	0.9568	24.30	0.1242	3.154	0.1188	76.64	483.4	2.150	486.1	2.162	4.069	28.06	**4.092**	**28.21**	**0.973**	**6.710**	0.4183	0.3703
	3-4	0.9588	24.35	0.1228	3.120	0.1178	75.98	549.3	2.443	559.5	2.489	4.664	32.16	**4.751**	**32.75**	**1.035**	**7.136**	0.4808	
	MEAN	***0.9562***	***24.29***	***0.1222***	***3.104***	***0.1168***	***75.38***	***538.3***	***2.395***	***541.2***	***2.408***	***4.605***	***31.75***	***4.629***	***31.92***	***0.999***	***6.888***	***0.4599***	***0.4715***
	COV	***0.34***	***0.34***	***2.24***	***2.24***	***2.33***	***2.33***	***15.19***	***15.19***	***15.57***	***15.57***	***14.73***	***14.73***	***15.06***	***15.06***	***3.76***	***3.76***	***15.52***	***17.42***

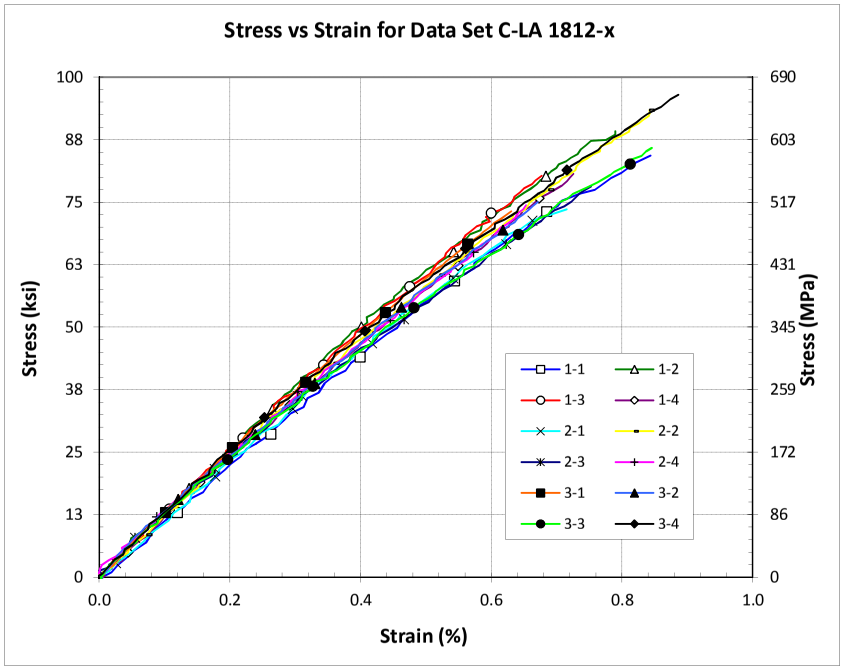
Note 1: Specimen misalignment lead to premature failure in the grip section.

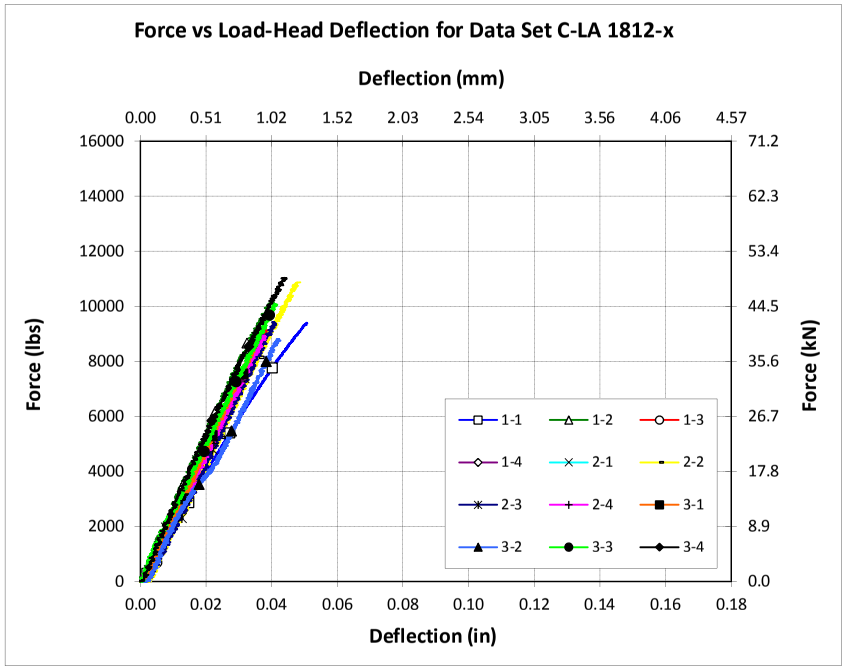




Compression Test Results Summary for the C-LA 1812-x Test Series

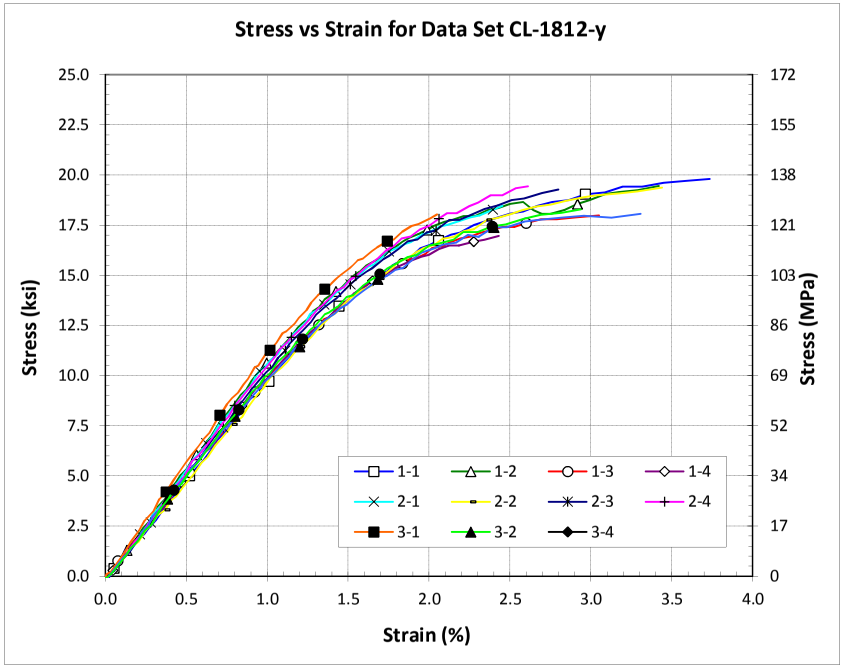
Notes	Specimen Number	Specimen Dimensions						Failure Load				Strength				Modulus		Failure		
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis		Strain	Local	Type
	#	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	Gage?	Code
	1-1	0.9550	24.26	0.1160	2.946	0.1108	71.46	9,338	41.54	9,394	41.79	84.31	581.3	**84.81**	**584.8**	**10.75**	**74.15**	0.844		
	1-2	0.9564	24.29	0.1187	3.014	0.1135	73.21	10,118	45.01	10,158	45.19	89.16	614.8	**89.52**	**617.2**	**12.70**	**87.55**	0.790		
	1-3	0.9523	24.19	0.1186	3.011	0.1129	72.84	9,064	40.32	9,135	40.64	80.28	553.5	**80.92**	**557.9**	**11.99**	**82.66**	0.677		
	1-4	0.9513	24.16	0.1157	2.939	0.1101	71.01	8,877	39.49	8,957	39.84	80.66	556.1	**81.38**	**561.1**	**11.61**	**80.05**	0.726		
	2-1	0.9551	24.26	0.1245	3.163	0.1189	76.74	8,745	38.90	8,853	39.38	73.52	506.9	**74.43**	**513.2**	**11.96**	**82.43**	0.716		
	2-2	0.9548	24.25	0.1214	3.083	0.1159	74.75	10,822	48.14	10,869	48.35	93.40	643.9	**93.80**	**646.7**	**11.78**	**81.24**	0.842		
	2-3	0.9543	24.24	0.1250	3.176	0.1193	76.97	9,327	41.49	9,428	41.94	78.18	539.0	**79.02**	**544.8**	**11.25**	**77.60**	0.752		
	2-4	0.9525	24.19	0.1248	3.171	0.1189	76.71	8,844	39.34	8,925	39.70	74.38	512.9	**75.06**	**517.5**	**11.33**	**78.14**	0.653		
	3-1	0.9551	24.26	0.1213	3.082	0.1159	74.77	8,481	37.73	8,616	38.33	73.18	504.6	**74.34**	**512.6**	**12.20**	**84.15**	0.631		
	3-2	0.9558	24.28	0.1223	3.105	0.1168	75.38	8,767	39.00	8,809	39.19	75.03	517.3	**75.40**	**519.8**	**11.19**	**77.14**	0.672		
	3-3	0.9530	24.21	0.1226	3.115	0.1169	75.40	10,031	44.62	10,066	44.77	85.82	591.7	**86.12**	**593.8**	**10.72**	**73.93**	0.846		
	3-4	0.9510	24.16	0.1191	3.024	0.1132	73.04	10,920	48.58	11,029	49.06	96.46	665.0	**97.41**	**671.6**	**12.03**	**82.97**	0.886		
	MEAN	***0.9539***	***24.23***	***0.1208***	***3.069***	***0.1153***	***74.36***	***9,445***	***42.01***	***9,520***	***42.35***	***82.03***	***565.6***	***82.69***	***570.1***	***11.63***	***80.17***	***0.753***		
	COV	***0.19***	***0.19***	***2.69***	***2.69***	***2.73***	***2.73***	***8.80***	***8.80***	***8.62***	***8.62***	***9.62***	***9.62***	***9.44***	***9.44***	***5.12***	***5.12***	***11.56***		

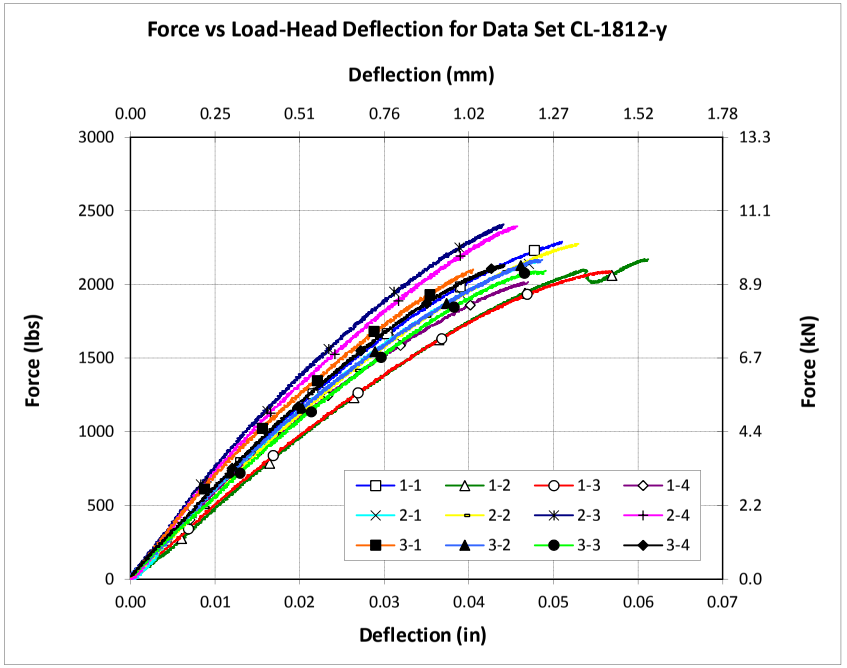




Compression Test Results Summary for the CL-1812-y Data Set

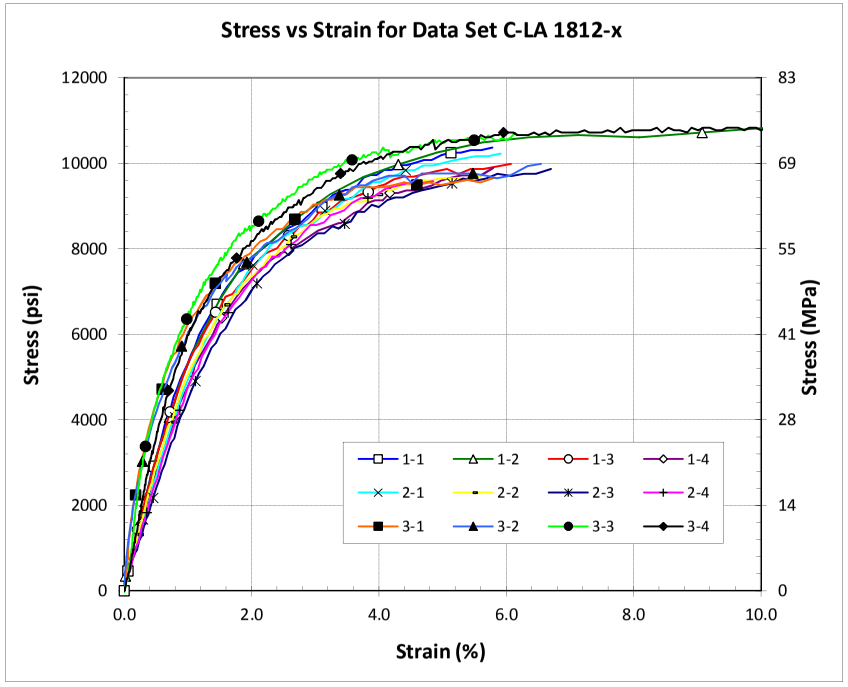
Notes	Specimen Number	Specimen Dimensions: Width		Thickness		Area		Failure Load: Aramis		Instron		Strength: Aramis		Instron		Modulus: Aramis		Failure: Strain	Local	Type
	#	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	Gage?	Code
	1-1	0.9539	24.23	0.1198	3.042	0.1142	73.69	2,263	10.07	2,290	10.19	19.81	136.6	**20.05**	138.2	**0.922**	6.360	3.73		
	1-2	0.9538	24.23	0.1161	2.949	0.1107	71.43	2,153	9.58	2,171	9.66	19.45	134.1	**19.61**	135.2	**1.014**	6.993	3.42		
	1-3	0.9525	24.19	0.1206	3.063	0.1149	74.11	2,065	9.19	2,089	9.29	17.98	124.0	**18.18**	125.4	**1.065**	7.345	3.05		
	1-4	0.9560	24.28	0.1233	3.132	0.1179	76.06	1,999	8.89	2,017	8.97	16.96	116.9	**17.11**	117.9	**0.937**	6.464	2.43		
	2-1	0.9544	24.24	0.1216	3.088	0.1160	74.85	2,142	9.53	2,163	9.62	18.46	127.3	**18.64**	128.5	**1.160**	8.000	2.45		
	2-2	0.9535	24.22	0.1219	3.096	0.1162	74.99	2,252	10.02	2,275	10.12	19.37	133.6	**19.57**	134.9	**1.037**	7.151	3.44		
	2-3	0.9536	24.22	0.1290	3.277	0.1230	79.39	2,373	10.55	2,408	10.71	19.28	132.9	**19.57**	134.9	**1.071**	7.384	2.80		
	2-4	0.9574	24.32	0.1281	3.254	0.1227	79.14	2,384	10.60	2,394	10.65	19.43	134.0	**19.52**	134.6	**1.118**	7.707	2.61		
	3-1	0.9620	24.43	0.1197	3.040	0.1151	74.28	2,076	9.23	2,100	9.34	18.03	124.3	**18.24**	125.8	**1.233**	8.501	2.05		
	3-2	0.9544	24.24	0.1193	3.029	0.1138	73.44			2,167	9.64			**19.03**	131.2					
	3-3	0.9554	24.27	0.1197	3.040	0.1143	73.76	2,065	9.19	2,092	9.30	18.06	124.5	**18.29**	126.1	**1.067**	7.357	3.31		
	3-4	0.9570	24.31	0.1205	3.060	0.1153	74.37	2,109	9.38	2,133	9.49	18.29	126.1	**18.51**	127.6	**1.053**	7.259	2.94		
	MEAN	***0.9553***	***24.26***	***0.1216***	***3.089***	***0.1162***	***74.96***	***2,171***	***9.657***	***2,191***	***9.748***	***18.65***	***128.6***	***18.86***	***130.0***	***1.062***	***7.320***	***2.93***		
	COV	***0.27***	***0.27***	***3.04***	***3.04***	***3.05***	***3.05***	***5.95***	***5.95***	***5.66***	***5.66***	***4.71***	***4.71***	***4.48***	***4.48***	***8.43***	***8.43***	***17.63***		

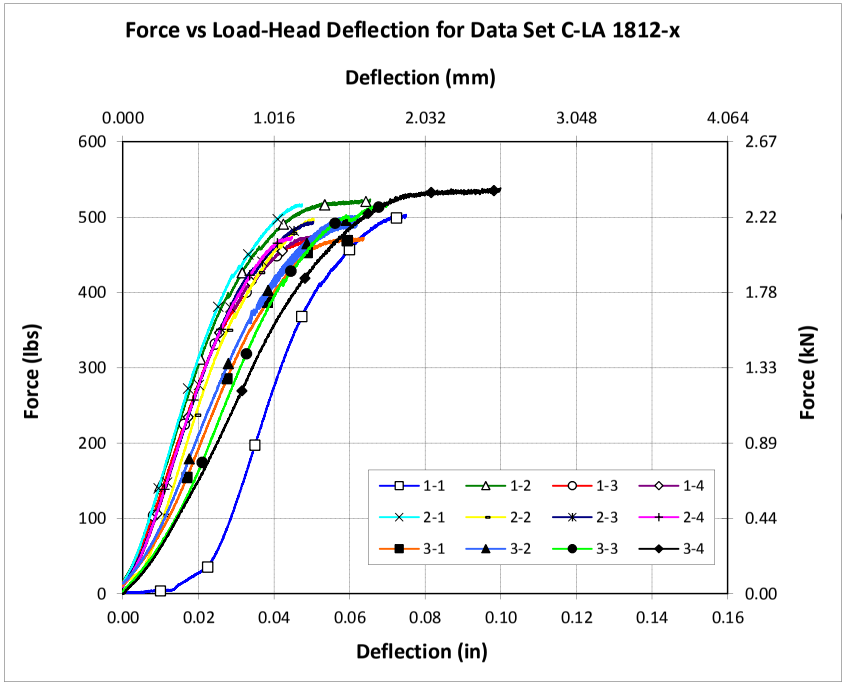




Shear Test Results Summary for the C-LA 1812-x Data Set

Notes	Specimen Number #	V-Notch Dimensions: Width in	Width mm	Thickness in	Thickness mm	Area in²	Area mm²	Failure Load: Aramis lbs.	Aramis kN	Instron lbs.	Instron kN	Max Strength: Aramis ksi	Aramis MPa	Instron ksi	Instron MPa	Modulus: Aramis ksi	Aramis Mpa	0.2% Offset: Strain %	Strength ksi	Strength MPa
	1-1	0.4070	10.34	0.1178	2.991	0.0479	30.93	496.9	2.211	502.9	2.237	10.37	71.48	**10.49**	**72.34**	**0.5824**	**4.016**	5.78	6.200	42.75
	1-2	0.4055	10.30	0.1188	3.018	0.0482	31.08	522.1	2.322	523.4	2.328	10.84	74.72	**10.86**	**74.91**	**0.5537**	**3.818**	10.18	6.400	44.13
	1-3	0.4003	10.17	0.1167	2.963	0.0467	30.12	466.2	2.074	469.3	2.088	9.99	68.85	**10.05**	**69.30**	**0.5619**	**3.875**	6.08	6.159	42.47
	1-4	0.4000	10.16	0.1193	3.029	0.0477	30.78	471.8	2.099	474.6	2.111	9.89	68.19	**9.95**	**68.60**	**0.5173**	**3.567**	5.80	5.800	39.99
	2-1	0.4040	10.26	0.1244	3.159	0.0502	32.41	513.7	2.285	516.9	2.299	10.22	70.49	**10.29**	**70.94**	**0.5170**	**3.565**	5.91	6.150	42.40
	2-2	0.4040	10.26	0.1260	3.201	0.0509	32.85	494.2	2.198	497.8	2.214	9.71	66.92	**9.78**	**67.41**	**0.5577**	**3.846**	5.60	5.800	39.99
	2-3	0.4005	10.17	0.1251	3.177	0.0501	32.31	494.2	2.198	493.6	2.196	9.87	68.02	**9.86**	**67.95**	**0.4519**	**3.116**	6.70	6.050	41.71
	2-4	0.4013	10.19	0.1220	3.098	0.0489	31.57	469.0	2.086	473.5	2.106	9.58	66.08	**9.68**	**66.71**	**0.4909**	**3.385**	4.85	6.000	41.37
	3-1	0.4025	10.22	0.1205	3.062	0.0485	31.30	469.0	2.086	472.7	2.103	9.67	66.65	**9.74**	**67.18**	**0.6263**	**4.318**	5.82	6.910	47.64
	3-2	0.4028	10.23	0.1235	3.137	0.0497	32.09	496.9	2.211	501.8	2.232	9.99	68.88	**10.09**	**69.55**	**0.5689**	**3.922**	6.55	7.100	48.95
	3-3	0.3990	10.13	0.1222	3.103	0.0487	31.45	522.1	2.322	519.5	2.311	10.71	73.85	**10.66**	**73.49**	**0.7967**	**5.494**	6.14	6.530	45.02
	3-4	0.4018	10.20	0.1232	3.129	0.0495	31.93	538.8	2.397	538.2	2.394	10.89	75.07	**10.88**	**74.98**	**0.7264**	**5.009**	10.62	6.100	42.06
	MEAN	***0.4024***	***10.22***	***0.1216***	***3.089***	***0.0489***	***31.57***	***496.3***	***2.207***	***498.7***	***2.218***	***10.14***	***69.93***	***10.19***	***70.28***	***0.5793***	***3.994***	***6.670***	***6.267***	***43.21***
	COV	***0.60***	***0.60***	***2.47***	***2.47***	***2.48***	***2.48***	***4.88***	***4.88***	***4.58***	***4.58***	***4.54***	***4.54***	***4.27***	***4.27***	***16.82***	***16.82***	***27.08***	***6.47***	***6.47***





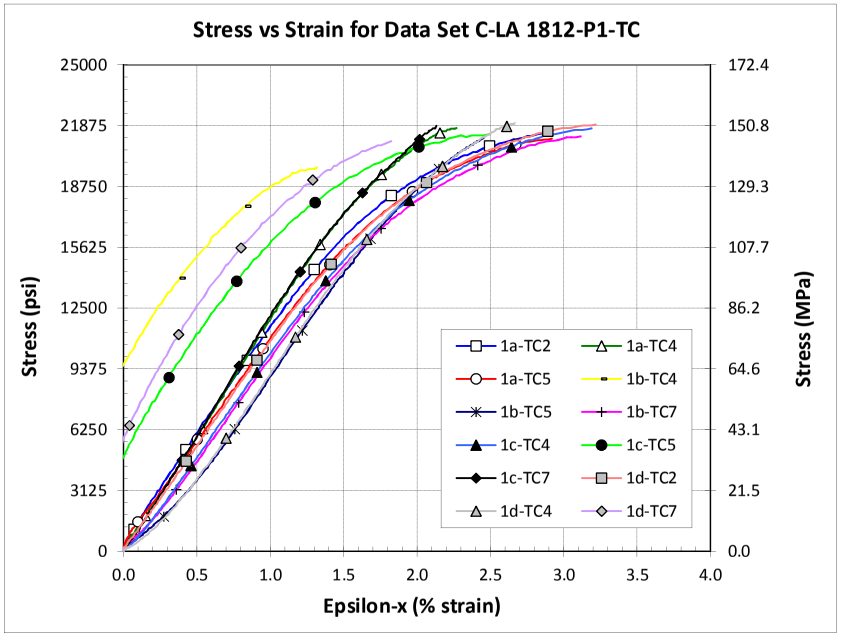
Through-Thickness Compression Test Results Summary for the C-LA 1812-P1 Data Set

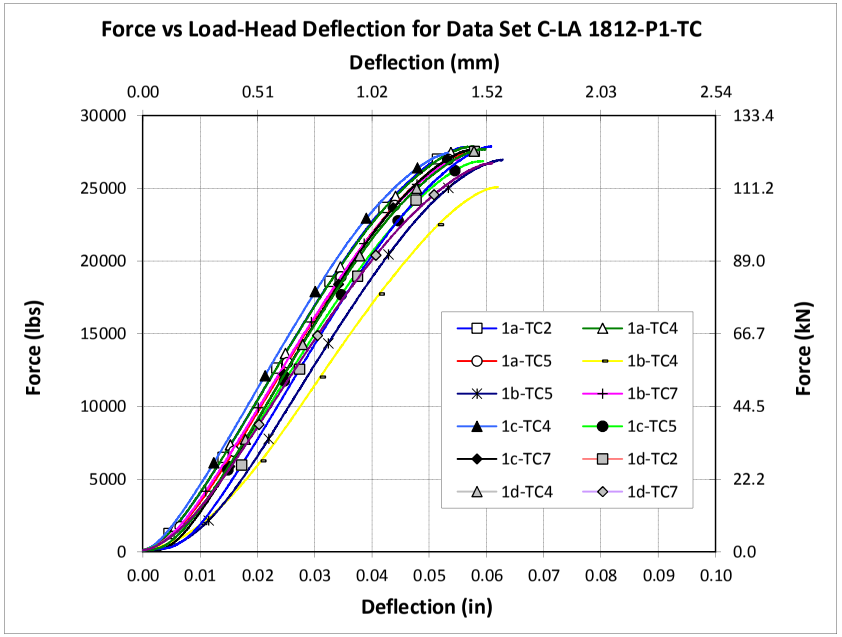
Notes	Specimen Number panel-spec.	Specimen Dimensions: Diameter in	Diameter mm	Thickness in	Thickness mm	Area in^2	Area mm^2	Failure Load: Aramis lbs.	Aramis kN	Instron lbs.	Instron kN	Strength: Aramis ksi	Aramis MPa	Instron ksi	Instron MPa	Modulus: Aramis Msi	Aramis GPa	Failure Strain %	Poisson's ν_{31}	Poisson's ν_{32}
1	1a-TC2	1.273	32.33	1.131	28.74	1.272	820.9	27,385	121.8	27,845	123.9	21.52	148.4	**21.88**	**150.9**	**1.097**	**7.567**	2.901		
2	1a-TC4	1.270	32.25	1.131	28.73	1.266	816.8	27,550	122.5	27,906	124.1	21.76	150.0	**22.04**	**152.0**	**1.226**	**8.455**	2.270		
1	1a-TC5	1.273	32.34	1.130	28.70	1.273	821.2	27,000	120.1	27,423	122.0	21.21	146.2	**21.54**	**148.5**	**1.034**	**7.130**	2.919		
2,3	1b-TC4	1.274	32.35	1.131	28.73	1.274	822.1	25,136	111.8	25,105	111.7	19.73	136.0	**19.70**	**135.8**	**1.152**	**7.946**	1.320	0.0385	0.6954
2	1b-TC5	1.272	32.31	1.129	28.68	1.271	819.7	27,000	120.1	26,982	120.0	21.25	146.5	**21.24**	**146.4**	**1.10**	**7.586**	2.455		
1	1b-TC7	1.270	32.25	1.130	28.69	1.266	817.1	27,000	120.1	27,044	120.3	21.32	147.0	**21.35**	**147.2**	**1.064**	**7.339**	3.116		
1	1c-TC4	1.268	32.20	1.076	27.34	1.262	814.4	27,440	122.1	27,460	122.1	21.74	149.9	**21.75**	**150.0**	**1.069**	**7.374**	3.190		
1,3	1c-TC5	1.264	32.11	1.077	27.36	1.255	809.9	26,925	119.8	26,884	119.6	21.45	147.9	**21.42**	**147.7**	**1.213**	**8.365**	2.498	0.7621	0.0470
2	1c-TC7	1.267	32.17	1.076	27.33	1.260	813.0	27,550	122.5	27,629	122.9	21.86	150.7	**21.93**	**151.2**	**1.245**	**8.584**	2.132		
1	1d-TC2	1.272	32.31	1.119	28.43	1.271	820.1	27,880	124.0	27,896	124.1	21.93	151.2	**21.95**	**151.3**	**1.088**	**7.499**	3.219		
2	1d-TC4	1.266	32.16	1.120	28.44	1.259	812.3	27,715	123.3	27,710	123.3	22.01	151.8	**22.01**	**151.7**	**1.115**	**7.687**	2.667		
2,3	1d-TC7	1.271	32.28	1.119	28.43	1.268	818.2	26,737	118.9	26,740	118.9	21.08	145.4	**21.08**	**145.4**	**1.361**	**9.387**	1.825	0.0454	0.4579
	MEAN	***1.270***	***32.25***	***1.114***	***28.30***	***1.266***	***816.7***	***27,110***	***120.6***	***27,219***	***121.1***	***21.41***	***147.6***	***21.49***	***148.2***	***1.147***	***7.910***	***2.543***	***0.0436***	***0.6385***
	COV	***0.23***	***0.23***	***2.07***	***2.07***	***0.46***	***0.46***	***2.64***	***2.64***	***2.87***	***2.87***	***2.85***	***2.85***	***3.03***	***3.03***	***8.36***	***8.36***	***23.0***	***10.3***	***25.0***

Note 1: The x-axis in Aramis is the 1-direction of the lamina.

Note 2: The x-axis in Aramis is the 2-direction of the lamina.

Note 3: Load mod



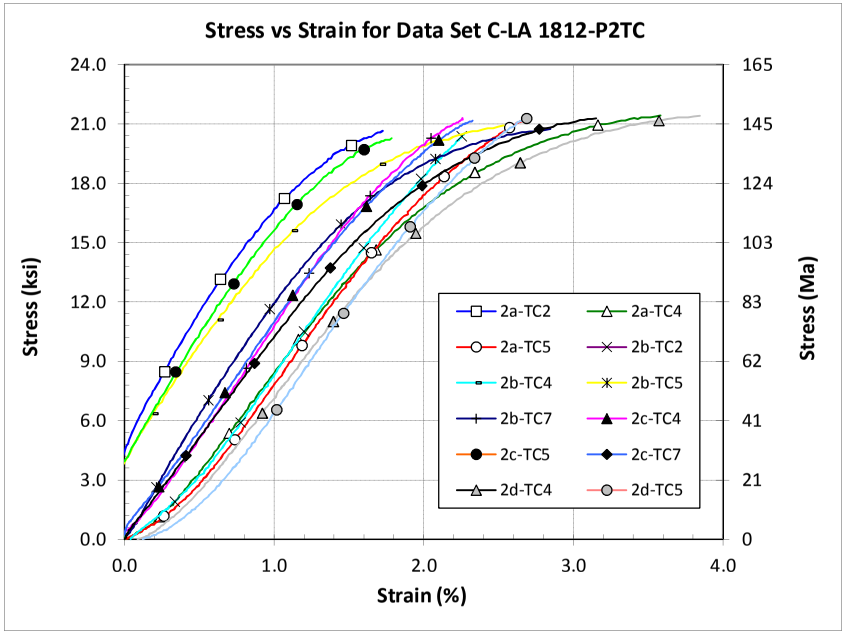


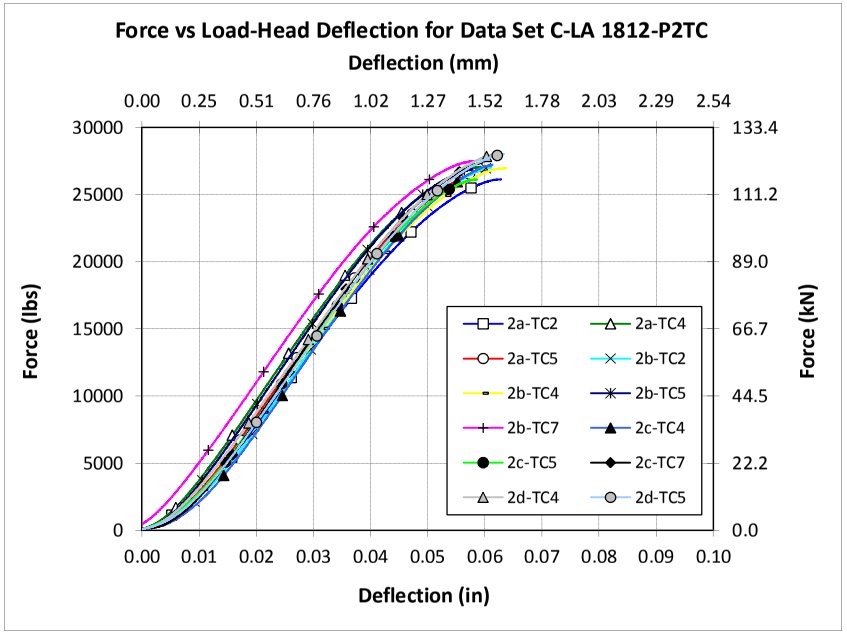
Through-Thickness Compression Test Results Summary for the C-LA 1812-P2 Data Set

Notes	Specimen Number	Specimen Dimensions						Failure Load				Strength				Modulus		Failure Strain	Poisson's	
		Diameter		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis				
	panel-spec.	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	ν_{31}	ν_{32}
2, 3	2a-TC2	1.270	32.27	1.190	30.22	1.267	817.7	26,172	116.4	26,140	116.3	20.65	142.4	**20.62**	**142.2**	**1.355**	**9.341**	1.727	**0.0534**	0.6379
1	2a-TC4	1.268	32.21	1.192	30.28	1.263	814.7	27,055	120.3	27,069	120.4	21.43	147.7	**21.44**	**147.8**	**1.004**	**6.925**	3.584		
2	2a-TC5	1.271	32.27	1.190	30.23	1.268	818.1	26,890	119.6	26,863	119.5	21.21	146.2	**21.18**	**146.1**	**1.062**	**7.322**	2.662		
2	2b-TC2	1.288	32.72	1.190	30.22	1.303	840.8	26,725	118.9	27,051	120.3	20.51	141.4	**20.76**	**143.1**	**1.102**	**7.601**	2.270		
1, 3	2b-TC4	1.282	32.56	1.189	30.21	1.291	832.8	27,019	120.2	26,976	120.0	20.93	144.3	**20.90**	**144.1**	**1.132**	**7.808**	2.536	0.8569	**0.0403**
1	2b-TC5	1.286	32.66	1.188	30.18	1.299	837.8	26,945	119.9	26,907	119.7	20.75	143.1	**20.72**	**142.9**	**1.332**	**9.183**	2.847		
1, 3	2b-TC7	1.284	32.62	1.187	30.15	1.295	835.5	27,584	122.7	27,503	122.3	21.30	146.9	**21.24**	**146.4**	**1.146**	**7.900**	2.258		
2	2c-TC4	1.278	32.47	1.133	28.77	1.283	828.0	27,165	120.8	27,232	121.1	21.17	145.9	**21.22**	**146.3**	**1.095**	**7.548**	2.327		
2, 3	2c-TC5	1.282	32.56	1.133	28.78	1.291	832.7	26,172	116.4	26,125	116.2	20.28	139.8	**20.24**	**139.6**	**1.257**	**8.668**	1.785	**0.0420**	0.6864
1	2c-TC7	1.280	32.51	1.131	28.72	1.286	829.9	27,385	121.8	27,397	121.9	21.29	146.8	**21.30**	**146.8**	**1.027**	**7.084**	3.152		
1	2d-TC4	1.284	32.60	1.192	30.27	1.294	834.8	27,715	123.3	28,089	124.9	21.42	147.7	**21.71**	**149.7**	**1.045**	**7.204**	3.846		
2	2d-TC5	1.284	32.61	1.195	30.34	1.295	835.4	27,660	123.0	28,023	124.7	21.36	147.3	**21.64**	**149.2**	**1.085**	**7.482**	2.714		
Panel 2	***MEAN***	***1.280***	***32.52***	***1.176***	***29.87***	***1.288***	***830.8***	***27,041***	***120.3***	***27,114***	***120.6***	***21.02***	***145.0***	***21.08***	***145.3***	***1.137***	***7.839***	***2.642***	***0.0452***	***0.7271***
	COV	***0.5%***	***0.5%***	***2.2%***	***2.2%***	***1.1%***	***1.1%***	***1.9%***	***1.9%***	***2.2%***	***2.2%***	***1.9%***	***1.9%***	***2.1%***	***2.1%***	***10%***	***10%***	***25%***	***16%***	***16%***
Panel 1 & 2	***MEAN***	***1.275***	***32.39***	***1.145***	***29.09***	***1.277***	***823.8***	***27,075***	***120.4***	***27,166***	***120.8***	***21.21***	***146.3***	***21.29***	***146.8***	***1.142***	***7.874***	***2.592***	***0.0444***	***0.6828***
	COV	***0.6%***	***0.6%***	***3.5%***	***3.5%***	***1.2%***	***1.2%***	***2.3%***	***2.3%***	***2.5%***	***2.5%***	***2.5%***	***2.5%***	***2.7%***	***2.7%***	***9.1%***	***9.1%***	***23%***	***12%***	***20%***

Note 1: The x-axis in Aramis is the 1-direction of the lamina.

Note 2: The x-axis in Aramis is the 2-direction of the lamina.



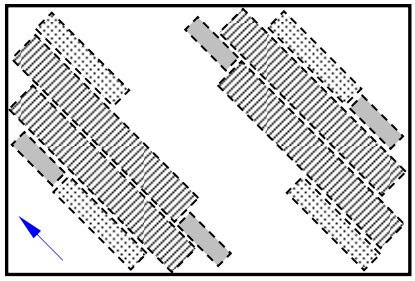


C-BX 1200 - Double Bias (±45°) *(0 / 0 / 50 / 50 / 0)*

In-Plane Properties

14” x 21” area (16” x 23” panel)

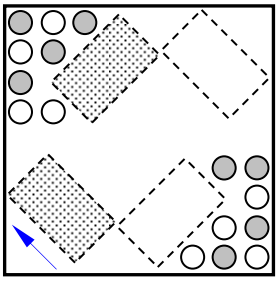
4 specimens/panel – 3 panels required



Through Thickness Properties

14” x 14” area (16” x 16” panel)

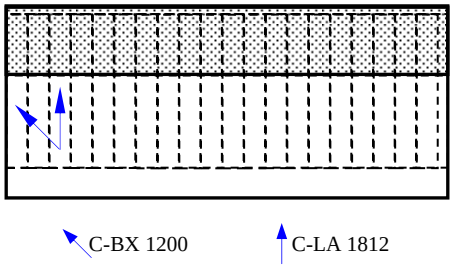
4 specimens/panel – 3 panels required



Fracture Properties

48” x 10” area (50” x 12” panel)

40 specimens/panel – 4 panels required



Thick ness	**0.16**	**0.99**	**0.182**
# of Layers	**10**	**62**	**3/45, 6/0**
50” Roll feet	**20**	**83**	**12**

Test	**Property**
Tension in 1-dir	E_{1t}, F_{1t}, v_{12} $E_{2t} = E_{1t}$ $F_{2t} = F_{1t}$
Comp. in 1 dir	E_{1c}, F_{1c}, v_{12} $E_{2c} = E_{1c}$, $F_{2c} = F_{1c}$
Shear in 12-dir	G_{12}, F_{12}

Test	**Property**
Tension in 3-dir	E_{3t}, F_{3t}, v_{31}, v_{32}
Comp. in 3-dir	E_{3c}, F_{3c}, v_{31}, v_{32}
Shear in 13-dir	G_{13}, F_{13}
Shear in 23-dir	G_{23}, F_{23}

F_{13} & F_{23} are larger than what would be obtained from tests in the 31 and 32 directions

Test	**Property**
Mode-I	$G_{1c\ onset}$, $G_{1c\ propagation}$
Mode-II	$G_{2c\ onset}$, $G_{2c\ propagation}$

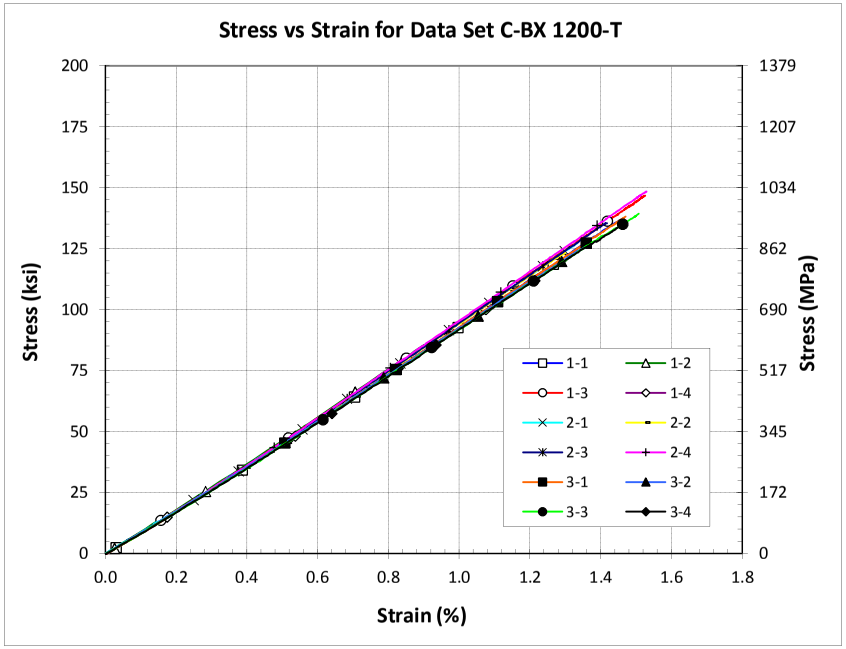
This is a mixed laminate with a C-BX 1200/C-LA 1812 interface.

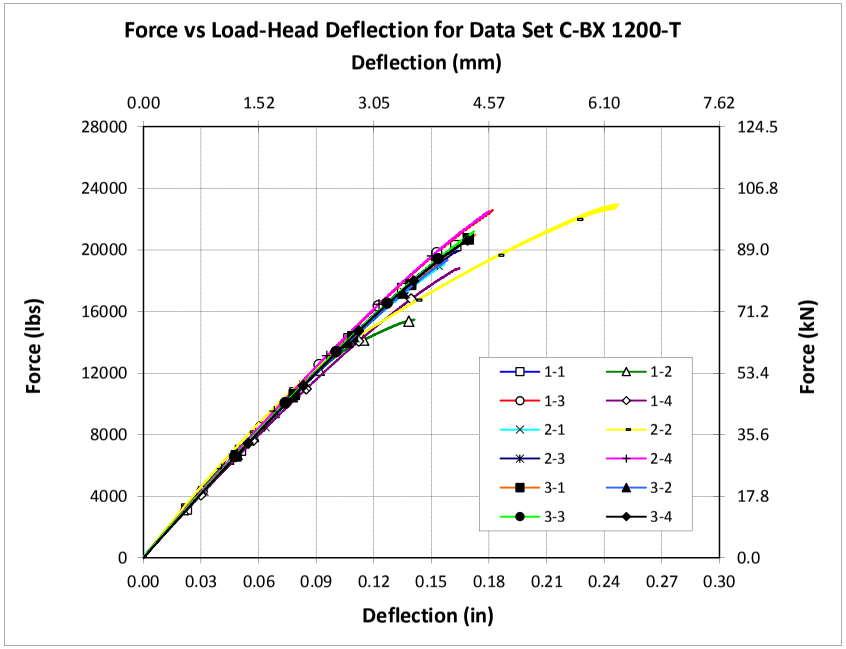
Tension Test Results Summary for the C-BX 1200 Data Set

Notes	Specimen Number panel-spec.	Specimen Gage Area Dimensions: Width in	Width mm	Thickness in	Thickness mm	Area in²	Area mm²	Failure Load: Aramis lbs.	Aramis kN	Instron lbs.	Instron kN	Strength: Aramis ksi	Aramis MPa	Instron ksi	Instron MPa	Modulus: Aramis Msi	Aramis GPa	Failure Strain %	Poisson's Ratio ν_{12}	Strain Range x 10⁻⁶
	1-1	0.9665	24.55	0.1571	3.990	0.1518	97.96	20,731	92.22	20,742	92.26	136.5	941.4	**136.6**	**941.9**	**8.942**	**61.65**	1.453	0.0570	994 to 2996
1	1-2	1.156	29.36	0.1558	3.958	0.1801	116.2	15,403	68.52	15,474	68.83	85.52	589.6	**85.91**	**592.3**	**9.228**	**63.63**	0.901		
	1-3	0.9648	24.50	0.1590	4.038	0.1534	98.95	22,489	100.0	22,594	100.5	146.6	1011	**147.3**	**1016**	**9.074**	**62.56**	1.526	0.0520	998 to 2988
	1-4	0.9681	24.59	0.1527	3.880	0.1479	95.40	18,798	83.62	18,815	83.70	127.1	876.5	**127.2**	**877.3**	**9.058**	**62.46**	1.357		
	2-1	0.9663	24.54	0.1548	3.931	0.1495	96.48	18,995	84.50	19,101	84.97	127.0	875.8	**127.7**	**880.7**	**8.975**	**61.88**	1.333	0.0472	986 to 2991
1	2-2	1.154	29.32	0.1580	4.014	0.1824	117.7	22,489	100.0	22,975	102.2	123.3	850.1	**126.0**	**868.5**	**9.182**	**63.31**	1.300		
2	2-2a	0.9654	24.52	0.1580	4.014	0.1526	98.42	19,094	84.94	19,113	85.02	125.2	863.0	**125.3**	**863.8**	**9.048**	**62.39**	1.314		
	2-3	0.9656	24.53	0.1524	3.871	0.1472	94.94	19,929	88.65	19,958	88.78	135.4	933.7	**135.6**	**935.1**	**9.137**	**63.00**	1.418	0.0533	986 to 2998
	2-4	0.9668	24.56	0.1565	3.975	0.1513	97.60	22,456	99.89	22,543	100.3	148.4	1023	**149.0**	**1027**	**9.241**	**63.71**	1.529		
	3-1	0.9699	24.63	0.1561	3.964	0.1514	97.66	20,907	93.00	20,979	93.32	138.1	952.3	**138.6**	**955.5**	**9.050**	**62.40**	1.471		
	3-2	0.9660	24.54	0.1588	4.033	0.1534	98.96	19,292	85.82	19,364	86.13	125.8	867.2	**126.2**	**870.4**	**8.874**	**61.19**	1.360		
	3-3	0.9634	24.47	0.1575	4.001	0.1517	97.90	21,149	94.07	21,198	94.29	139.4	961.0	**139.7**	**963.2**	**8.947**	**61.69**	1.508	0.0501	994 to 2999
	3-4	0.9639	24.48	0.1601	4.067	0.1543	99.58	20,610	91.68	20,752	92.31	135.8	920.7	**134.4**	**927.0**	**8.862**	**61.10**	1.448		
	MEAN	***0.9661***	***24.54***	***0.1565***	***3.975***	***0.1512***	***97.54***	***20,536***	***91.35***	***20,605***	***91.65***	***136.0***	***936.3***	***136.3***	***939.4***	***9.016***	***62.16***	***1.440***	***0.0506***	
	COV	***0.20***	***0.20***	***1.65***	***1.65***	***1.56***	***1.56***	***6.36***	***6.36***	***6.40***	***6.40***	***5.74***	***5.78***	***5.79***	***5.79***	***1.32***	***1.32***	***4.99***	***5.22***	

Note 1: These specimens were tested with a larger specimen gage-width, which did not lead to proper specimen failures on the 22-Kip test frame. They are not included in the calculation of the Mean. (The gage-width was reduced on the remaining specimens.

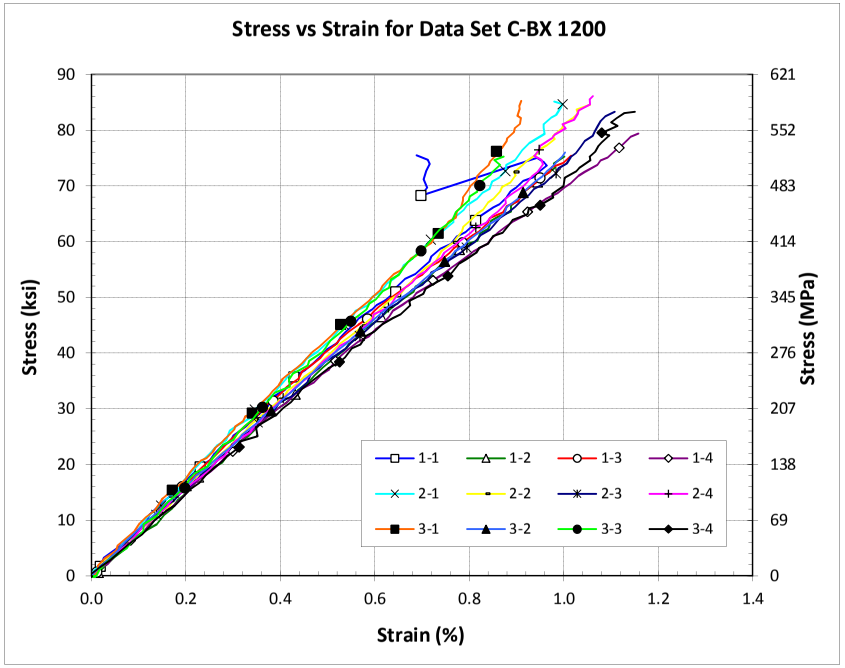
Note 2: This was a re-test of a specimen after the gage width had been reduced, since it had not failed when previously tested with the larger gage width. It is not included in the calculation of the Mean.

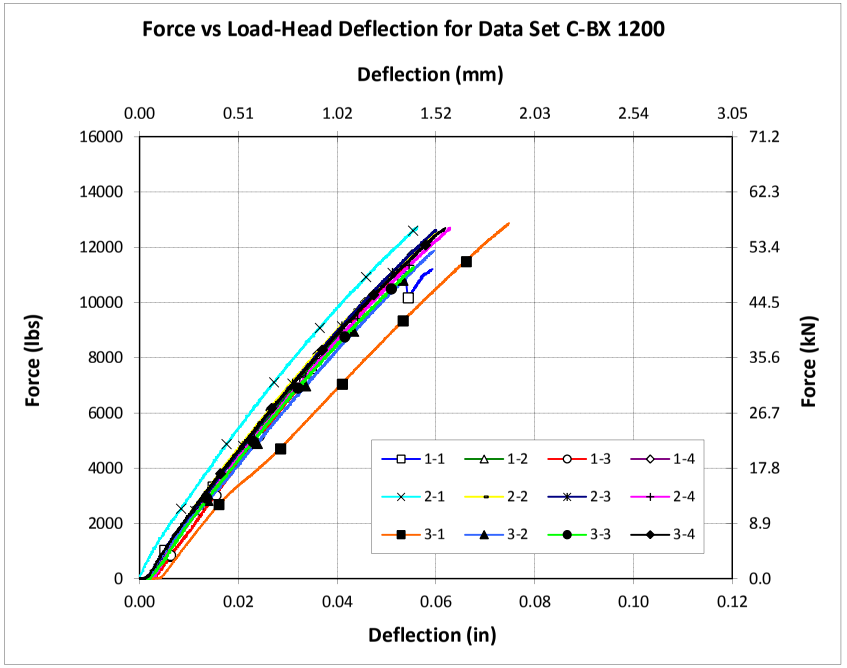




Compression Test Results Summary for the C-BX 1200 Data Set

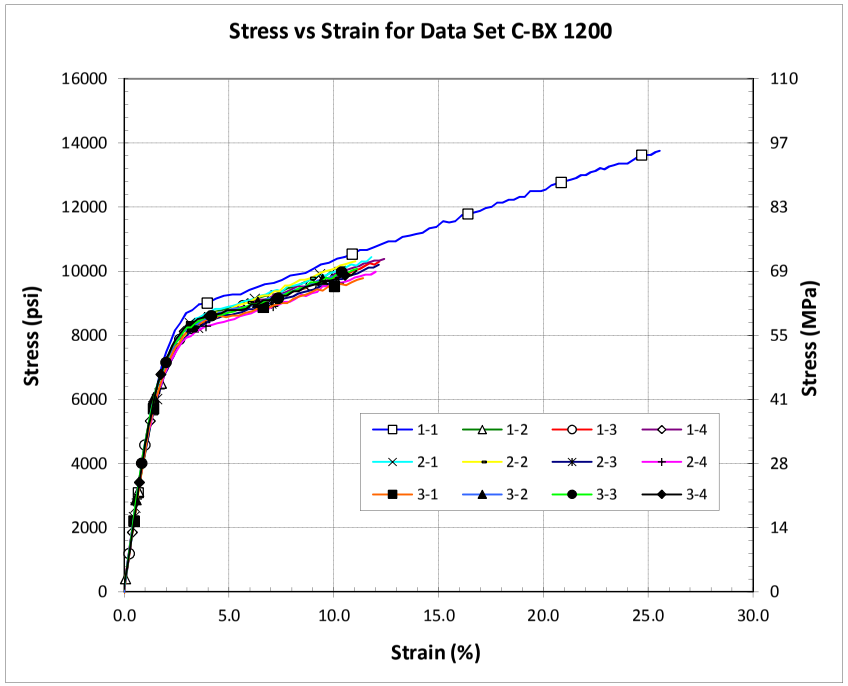
Notes	Specimen Number	Specimen Dimensions						Failure Load				Strength				Modulus		Failure		
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis		Strain	Local	Type
	panel-spec.	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	Gage?	Code
	1-1	0.9524	24.19	0.1549	3.936	0.1476	95.2	11,138	49.54	11,206	49.84	75.48	520.4	**75.94**	**523.6**	**8.375**	**57.74**	0.688		
	1-2	0.9548	24.25	0.1582	4.018	0.1510	97.4	11,369	50.57	11,462	50.99	75.28	519.0	**75.90**	**523.3**	**7.734**	**53.33**	1.002		
	1-3	0.9510	24.16	0.1563	3.970	0.1487	95.9	11,215	49.89	11,363	50.55	75.44	520.2	**76.44**	**527.0**	**8.314**	**57.32**	1.015		
	1-4	0.9526	24.20	0.1576	4.003	0.1501	96.9	11,918	53.01	11,972	53.25	79.39	547.4	**79.75**	**549.9**	**7.830**	**53.99**	1.158		
	2-1	0.9521	24.18	0.1564	3.973	0.1489	96.1	12,676	56.39	12,737	56.66	85.11	586.8	**85.52**	**589.6**	**8.590**	**59.23**	0.980		
	2-2	0.9508	24.15	0.1561	3.966	0.1484	95.8	12,555	55.85	12,578	55.95	84.58	583.1	**84.73**	**584.2**	**8.055**	**55.54**	1.056		
	2-3	0.9529	24.20	0.1575	4.000	0.1501	96.8	12,500	55.60	12,626	56.16	83.30	574.4	**84.14**	**580.1**	**7.798**	**53.77**	1.108		
	2-4	0.9518	24.17	0.1538	3.906	0.1463	94.4	12,599	56.04	12,715	56.56	86.09	593.6	**86.89**	**599.1**	**7.862**	**54.21**	1.062		
	3-1	0.9508	24.15	0.1583	4.020	0.1505	97.1	12,830	57.07	12,873	57.26	85.26	587.9	**85.55**	**589.9**	**8.449**	**58.25**	0.910		
	3-2	0.9526	24.20	0.1621	4.116	0.1544	99.6	11,731	52.18	11,876	52.82	75.99	523.9	**76.92**	**530.3**	**7.553**	**52.07**	1.003		
	3-3	0.9519	24.18	0.1560	3.963	0.1485	95.8	11,171	49.69	11,285	50.20	75.23	518.7	**76.00**	**524.0**	**8.625**	**59.47**	0.873		
	3-4	0.9516	24.17	0.1588	4.033	0.1511	97.5	12,588	55.99	12,699	56.49	83.31	574.4	**84.04**	**579.5**	**7.630**	**52.61**	1.151		
	MEAN	***0.9521***	***24.18***	***0.1572***	***3.992***	***0.1496***	***96.5***	***12,024***	***53.49***	***12,116***	***53.89***	***80.37***	***554.1***	***80.98***	***558.4***	***8.068***	***55.63***	***1.000***		
	COV	***0.12***	***0.12***	***1.35***	***1.35***	***1.38***	***1.38***	***5.56***	***5.56***	***5.41***	***5.41***	***5.75***	***5.75***	***5.58***	***5.58***	***4.76***	***4.76***	***13.08***		

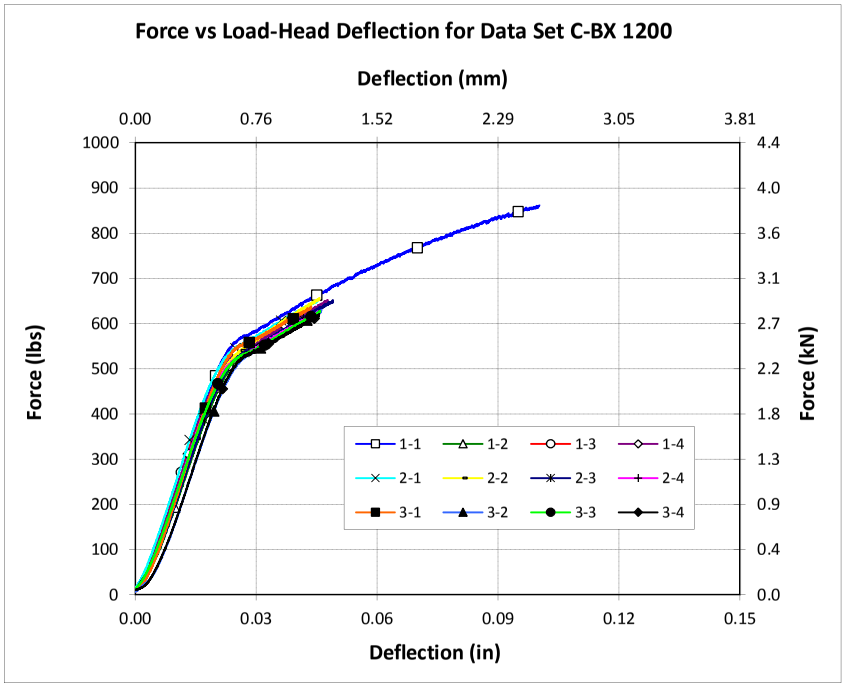




Shear Test Results Summary for the C-BX 1200 Data Set

Notes	Specimen Number	V-Notch Dimensions						Maximum Load				Strength at Max Load				Modulus		0.2% Offset		
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis		Strain	Strength	
	panel-spec.	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	ksi	Mpa	%	ksi	MPa
	1-1	0.4018	10.20	0.1551	3.940	0.0623	40.20	857.1	3.813	860.8	3.829	13.76	94.84	13.81	95.25	**0.4535**	**3.127**	1.690	**6.700**	**46.20**
	1-2	0.3945	10.02	0.1556	3.952	0.0614	39.60	622.6	2.769	626.0	2.785	10.14	69.93	10.20	70.32	**0.4388**	**3.026**	1.600	**6.050**	**41.71**
	1-3	0.3950	10.03	0.1544	3.923	0.0610	39.36	628.2	2.794	631.8	2.810	10.30	71.00	10.36	71.41	**0.4918**	**3.391**	1.400	**5.900**	**40.68**
	1-4	0.3980	10.11	0.1555	3.949	0.0619	39.93	642.1	2.856	651.8	2.900	10.38	71.54	10.53	72.62	**0.4594**	**3.168**	1.557	**6.226**	**42.93**
	2-1	0.3975	10.10	0.1568	3.982	0.0623	40.21	650.5	2.894	652.9	2.904	10.44	71.97	10.48	72.24	**0.4758**	**3.281**	1.430	**5.810**	**40.06**
	2-2	0.3960	10.06	0.1586	4.029	0.0628	40.53	647.7	2.881	656.2	2.919	10.31	71.09	10.45	72.03	**0.4414**	**3.044**	1.597	**6.170**	**42.54**
	2-3	0.3958	10.05	0.1584	4.024	0.0627	40.45	639.3	2.844	651.7	2.899	10.20	70.31	10.39	71.67	**0.4497**	**3.101**	1.465	**5.700**	**39.30**
	2-4	0.3970	10.08	0.1579	4.010	0.0627	40.44	625.4	2.782	627.6	2.792	9.98	68.79	10.01	69.04	**0.4518**	**3.115**	1.530	**5.990**	**41.30**
	3-1	0.4015	10.20	0.1607	4.081	0.0645	41.62	631.0	2.807	637.6	2.836	9.78	67.43	9.88	68.14	**0.4481**	**3.089**	1.564	**6.102**	**42.07**
	3-2	0.3948	10.03	0.1575	4.000	0.0622	40.11	622.6	2.769	630.5	2.804	10.02	69.05	10.14	69.93	**0.4986**	**3.438**	1.401	**5.900**	**40.68**
	3-3	0.3970	10.08	0.1544	3.921	0.0613	39.54	617.0	2.745	627.5	2.791	10.07	69.41	10.24	70.59	**0.4793**	**3.305**	1.515	**6.286**	**43.34**
	3-4	0.3968	10.08	0.1547	3.929	0.0614	39.59	614.2	2.732	620.8	2.762	10.01	69.00	10.12	69.74	**0.4448**	**3.067**	1.692	**6.670**	**45.99**
	MEAN	***0.3971***	***10.09***	***0.1566***	***3.978***	***0.0622***	***40.13***	***649.8***	***2.890***	***656.3***	***2.919***	***10.45***	***72.03***	***10.55***	***72.75***	***0.4611***	***3.179***	***1.537***	***6.125***	***42.23***
	COV	***0.60***	***0.60***	***1.28***	***1.28***	***1.53***	***1.53***	***10.21***	***10.21***	***10.00***	***10.00***	***10.14***	***10.14***	***9.92***	***9.92***	***4.38***	***4.38***	***6.52***	***5.09***	***5.09***



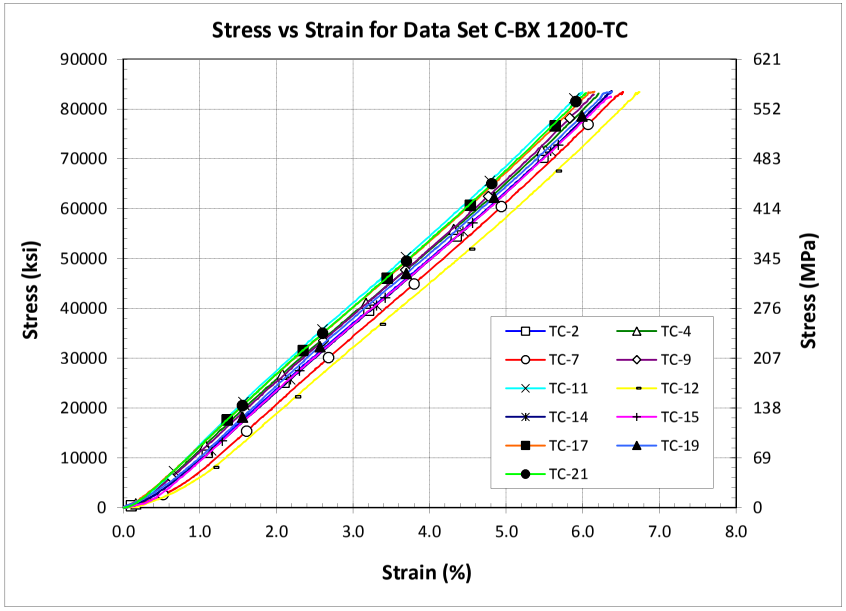


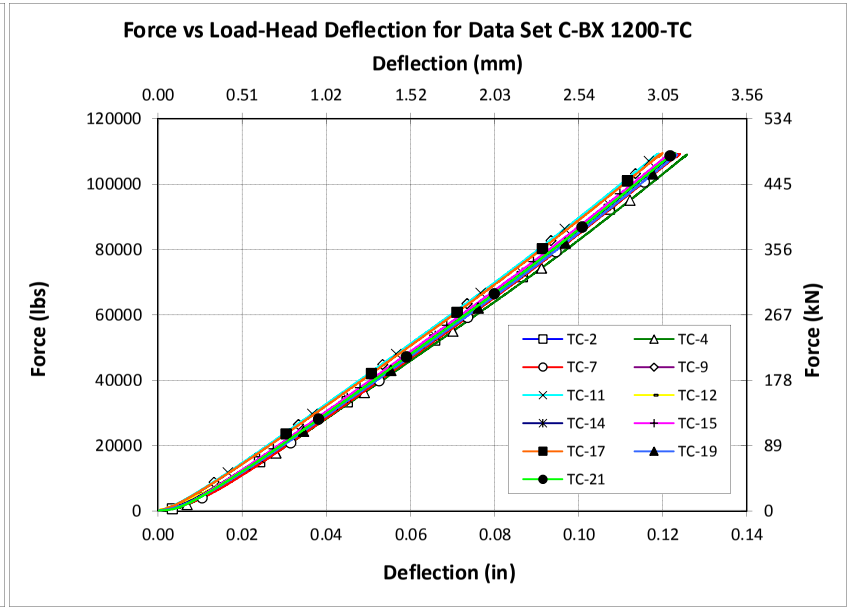
Through-Thickness Compression Test Results Summary for the C-BX 1200 Data Set

Notes	Specimen Number	Specimen Dimensions						Maximum Load				Strength at Max Load				Modulus		Failure Strain	Poisson's	
		Diameter		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis			ν_{31}	ν_{32}
	#	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%		
1	TC-2	1.291	32.80	0.9624	24.45	1.310	844.8	108,936	484.6	109,128	485.4	83.19	573.6	**83.33**	**574.6**	**1.419**	**9.784**	6.366	0.0857	0.0859
2	TC-4	1.292	32.80	0.9645	24.50	1.310	845.2	108,881	484.3	109,139	485.5	83.11	573.0	**83.31**	**574.4**	**1.443**	**9.947**	6.208		
2	TC-7	1.289	32.73	0.9584	24.34	1.304	841.6	108,771	483.8	109,206	485.8	83.38	574.9	**83.72**	**577.2**	**1.387**	**9.566**	6.527	0.0985	0.1081
1	TC-9	1.292	32.82	0.9588	24.35	1.312	846.2	108,716	483.6	109,096	485.3	82.89	571.5	**83.18**	**573.5**	**1.402**	**9.669**	6.143		
1	TC-11	1.293	32.84	0.9571	24.31	1.313	846.9	109,376	486.5	109,355	486.4	83.32	574.5	**83.30**	**574.4**	**1.511**	**10.42**	5.999		
1	TC-12	1.290	32.77	0.9570	24.31	1.307	843.3	109,046	485.1	109,303	486.2	83.42	575.2	**83.62**	**576.5**	**1.344**	**9.268**	6.741	0.0827	0.0865
2	TC-14	1.289	32.73	0.9578	24.33	1.304	841.4	108,991	484.8	109,501	487.1	83.57	576.2	**83.97**	**578.9**	**1.360**	**9.376**	6.380		
2	TC-15	1.294	32.87	0.9581	24.34	1.315	848.7	108,551	482.9	109,239	485.9	82.52	569.0	**83.04**	**572.6**	**1.418**	**9.775**	6.371	0.0874	0.0978
1	TC-17	1.290	32.76	0.9563	24.29	1.307	843.1	109,046	485.1	109,524	487.2	83.44	575.3	**83.81**	**577.8**	**1.458**	**10.05**	6.152		
1	TC-19	1.288	32.71	0.9600	24.38	1.302	840.2	108,606	483.1	108,946	484.6	83.40	575.0	**83.66**	**576.8**	**1.453**	**10.02**	6.378	0.0877	0.1030
2	TC-21	1.291	32.78	0.9616	24.42	1.308	844.1	108,881	484.3	109,618	487.6	83.22	573.8	**83.78**	**577.7**	**1.486**	**10.25**	6.046		
	MEAN	***1.291***	***32.78***	***0.9586***	***24.35***	***1.308***	***843.9***	***108,891***	***484.4***	***109,278***	***486.1***	***83.23***	***573.8***	***83.52***	***575.9***	***1.426***	***9.829***	***6.301***	***0.0924***	***0.0923***
	COV	***0.15***	***0.15***	***0.24***	***0.24***	***0.29***	***0.29***	***0.21***	***0.21***	***0.19***	***0.19***	***0.36***	***0.36***	***0.36***	***0.36***	***3.6***	***3.6***	***3.5***	***11.3***	***8.6***

Note 1: The x-axis in Aramis is the 1-direction of the lamina.

Note 2:The x-axis in Aramis is the 2-direction of the lamina.



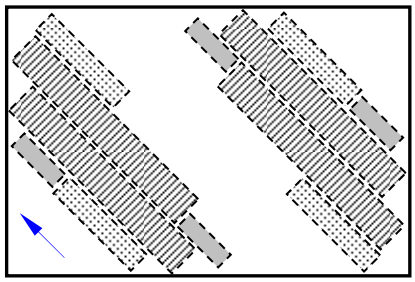


C-BX 1800 - Double Bias (±45°) *(0 / 0 / 50 / 50 / 0)*

In-Plane Properties

14” x 21” area (16” x 23” panel)

4 specimens/panel – 3 panels required



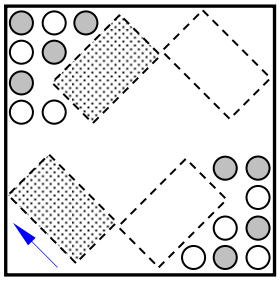
Thick ness	**0.16**
# of Layers	**7**
50” Roll feet	**14**

Test	Property
Tension in 1-dir	E_{1t}, F_{1t}, v_{12}
	$E_{2t} = E_{1t}$ $F_{2t} = F_{1t}$
Comp. in 1 dir	E_{1c}, F_{1c}, v_{12}
	$E_{2c} = E_{1c}$, $F_{2c} = F_{1c}$
Shear in 12-dir	G_{12}, F_{12}

Through Thickness Properties

14” x 14” area (16” x 16” panel)

4 specimens/panel – 3 panels required



1.01	
44	
59	

Test	Property
Tension in 3-dir	E_{3t}, F_{3t}, v_{31}, v_{32}
Comp. in 3-dir	E_{3c}, F_{3c}, v_{31}, v_{32}
Shear in 13-dir	G_{13}, F_{13}
Shear in 23-dir	G_{23}, F_{23}

F_{13} & F_{23} are larger than what would be obtained from tests in the 31 and 32 directions

Fracture Properties

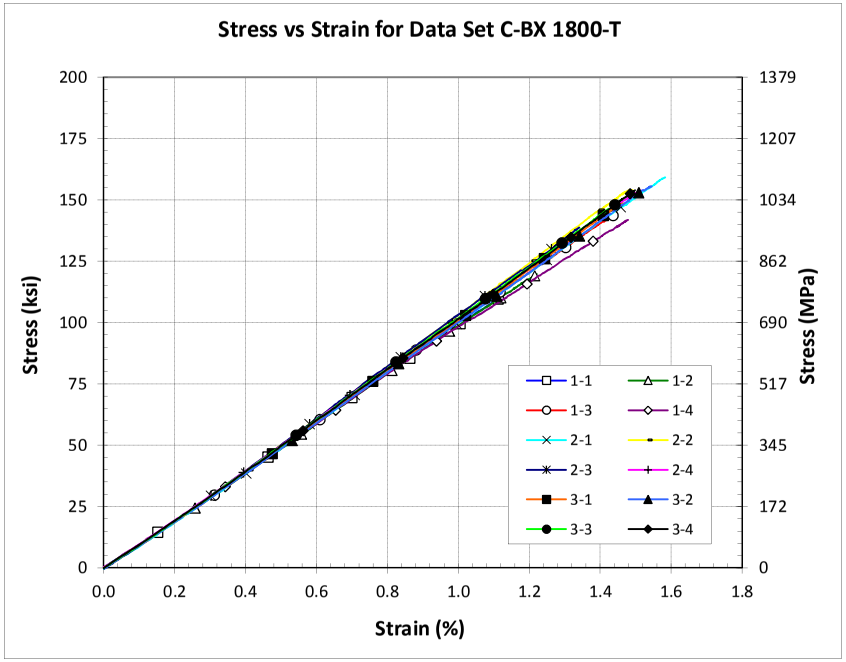
Not Required

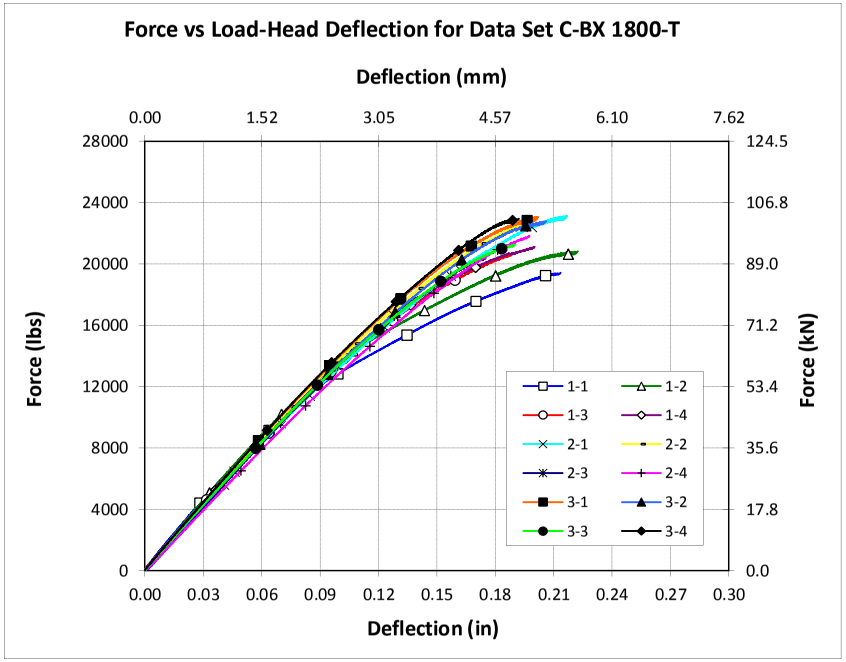
Tension Test Results Summary for the C-BX 1800 Data Set

Notes	Specimen Number panel-spec.	Specimen Gage Area Dimensions: Width in	Width mm	Thickness in	Thickness mm	Area in²	Area mm²	Failure Load: Aramis lbs.	Aramis kN	Instron lbs.	Instron kN	Strength: Aramis ksi	Aramis MPa	Instron ksi	Instron MPa	Modulus: Aramis Msi	Aramis GPa	Failure Strain %	Poisson's Ratio ν_{12}	Strain Range (x10⁻⁶)
1	1-1	1.1513	29.24	0.1525	3.875	0.1756	113.3	19,358	86.11	19,421	86.39	110.2	760.0	**110.6**	**762.5**	**9.776**	**67.41**	1.120	0.0462	983 to 2995
1	1-2	1.1508	29.23	0.1505	3.824	0.1732	111.8	20,742	92.27	20,819	92.61	119.7	825.6	**120.2**	**828.6**	**9.705**	**66.92**	1.222		
	1-3	0.9671	24.56	0.1491	3.788	0.1442	93.06	20,709	92.12	20,761	92.35	143.6	989.9	**143.9**	**992.4**	**9.788**	**67.49**	1.437	0.0497	992 to 2995
	1-4	0.9699	24.63	0.1529	3.884	0.1483	95.68	21,028	93.54	21,105	93.88	141.8	977.6	**142.3**	**981.2**	**9.628**	**66.38**	1.478		
2	2-1	0.9641	24.49	0.1465	3.722	0.1413	91.14	22,489	100.0	23,131	102.9	159.2	1098	**163.7**	**1129**	**9.939**	**68.53**	1.583	0.0567	998 to 2992
	2-2	0.9668	24.56	0.1508	3.831	0.1458	94.06	22,467	99.94	22,554	100.3	154.1	1062	**154.7**	**1067**	**9.863**	**68.00**	1.491		
	2-3	0.9704	24.65	0.1513	3.842	0.1468	94.70	20,358	90.56	20,384	90.67	138.7	956.2	**138.9**	**957.5**	**10.05**	**69.28**	1.341	0.0580	998 to 2997
	2-4	0.9703	24.64	0.1456	3.698	0.1413	91.13	21,731	96.66	21,819	97.06	153.8	1061	**154.5**	**1065**	**9.892**	**68.20**	1.516		
2	3-1	0.9850	25.02	0.1536	3.902	0.1513	97.63	22,489	100.0	23,060	102.6	148.6	1025	**152.4**	**1051**	**9.752**	**67.24**	1.465		
2	3-2	0.9786	24.86	0.1477	3.752	0.1446	93.26	22,489	100.0	22,783	101.3	155.6	1073	**157.6**	**1087**	**9.775**	**67.40**	1.546		
	3-3	0.9690	24.61	0.1462	3.713	0.1416	91.38	21,248	94.51	21,281	94.66	150.0	1034	**150.2**	**1036**	**9.867**	**68.03**	1.460	0.0536	995 to 2996
2	3-4	0.9676	24.58	0.1510	3.835	0.1461	94.25	22,489	100.0	22,946	102.1	153.9	1061	**157.1**	**1083**	**9.885**	**68.16**	1.499		
	MEAN	***0.9709***	***24.66***	***0.1495***	***3.797***	***0.1451***	***93.63***	***21,750***	***96.75***	***21,982***	***97.78***	***149.9***	***1034***	***151.5***	***1045***	***9.844***	***67.87***	***1.482***	***0.0545***	
	COV	***0.64***	***0.64***	***1.92***	***1.92***	***2.25***	***2.25***	***3.91***	***3.91***	***4.73***	***4.73***	***4.45***	***4.45***	***5.12***	***5.12***	***1.17***	***1.17***	***4.41***	***6.80***	

Note 1: Specimens 1 & 2 started to slip in the grips, so these results are excluded from the calculations for the Mean and COV.

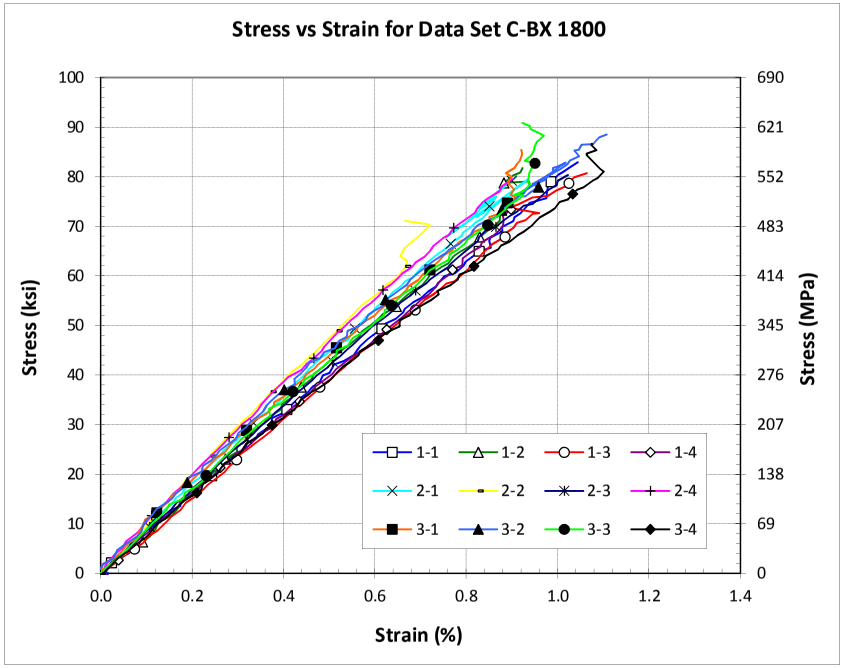
Note 2: Aramis clipped at 10 volts on the analog input for the load resulting in an erroneous Failure Load of 22,489 for these specimens.

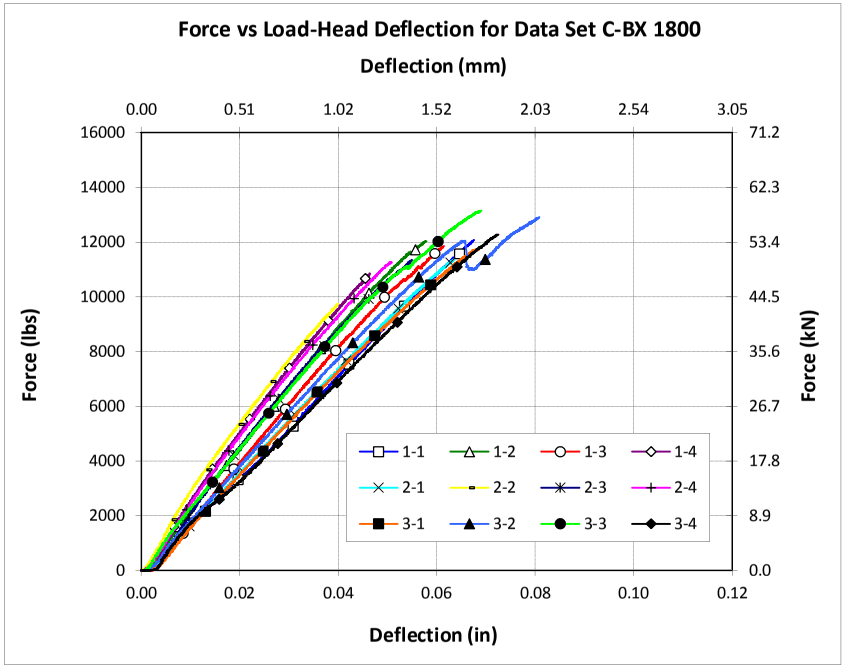




Compression Test Results Summary for the C-BX 1800 Data Set

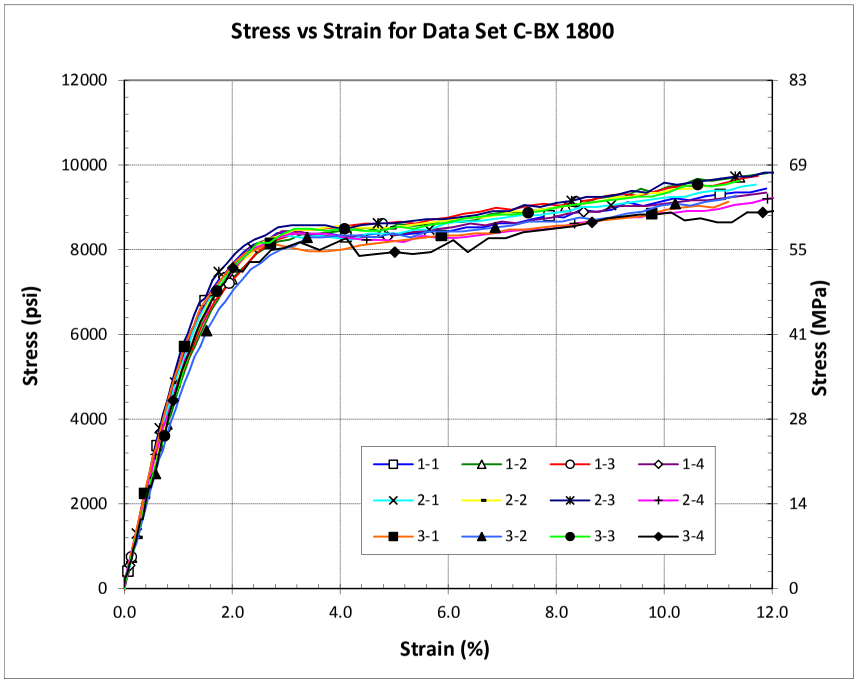
Notes	Specimen Number	Specimen Dimensions						Failure Load				Strength				Modulus		Failure		
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis		Strain	Local	Type
	#	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	Gage?	Code
	1-1	0.9506	24.15	0.1530	3.885	0.1454	93.8	12,061	53.65	12,080	53.73	82.94	571.9	**83.07**	**572.8**	**7.725**	**53.26**	1.045		
	1-2	0.9521	24.18	0.1539	3.910	0.1466	94.6	11,984	53.31	12,041	53.56	81.76	563.7	**82.15**	**566.4**	**9.297**	**64.10**	0.923		
	1-3	0.9505	24.14	0.1535	3.898	0.1459	94.1	11,775	52.38	11,851	52.71	80.72	556.6	**81.24**	**560.1**	**8.091**	**55.79**	1.064		
	1-4	0.9479	24.08	0.1535	3.898	0.1455	93.9	10,831	48.18	10,852	48.27	74.45	513.3	**74.59**	**514.3**	**7.952**	**54.83**	0.902		
	2-1	0.9514	24.16	0.1485	3.771	0.1412	91.1	11,303	50.28	11,371	50.58	80.03	551.8	**80.52**	**555.1**	**9.053**	**62.42**	0.909		
	2-2	0.9550	24.26	0.1432	3.637	0.1368	88.2	9,721	43.24	9,743	43.34	71.08	490.1	**71.24**	**491.2**	**9.918**	**68.39**	0.666		
	2-3	0.9505	24.14	0.1472	3.738	0.1399	90.2	11,237	49.98	11,345	50.46	80.34	553.9	**81.11**	**559.3**	**8.371**	**57.72**	1.023		
	2-4	0.9509	24.15	0.1488	3.780	0.1415	91.3	11,248	50.03	11,273	50.14	79.48	548.0	**79.65**	**549.2**	**9.334**	**64.36**	0.901		
	3-1	0.9499	24.13	0.1439	3.656	0.1367	88.2	11,676	51.94	11,764	52.33	85.40	588.8	**86.04**	**593.2**	**8.627**	**59.48**	0.920		
	3-2	0.9446	23.99	0.1530	3.886	0.1445	93.2	12,797	56.92	12,916	57.45	88.54	610.5	**89.37**	**616.2**	**8.777**	**60.52**	1.107		
	3-3	0.9491	24.11	0.1519	3.859	0.1442	93.0	13,104	58.29	13,145	58.47	90.87	626.5	**91.15**	**628.5**	**8.717**	**60.11**	0.923		
	3-4	0.9476	24.07	0.1486	3.774	0.1408	90.8	12,204	54.28	12,273	54.59	86.66	597.5	**87.16**	**600.9**	**8.197**	**56.52**	1.075		
	MEAN	***0.9500***	***24.13***	***0.1499***	***3.808***	***0.1424***	***91.9***	***11,662***	***51.87***	***11,721***	***52.14***	***81.86***	***564.4***	***82.27***	***567.3***	***8.672***	***59.79***	***0.955***		
	COV	***0.27***	***0.27***	***2.53***	***2.53***	***2.42***	***2.42***	***7.70***	***7.70***	***7.78***	***7.78***	***6.85***	***6.85***	***6.96***	***6.96***	***7.47***	***7.47***	***12.49***		

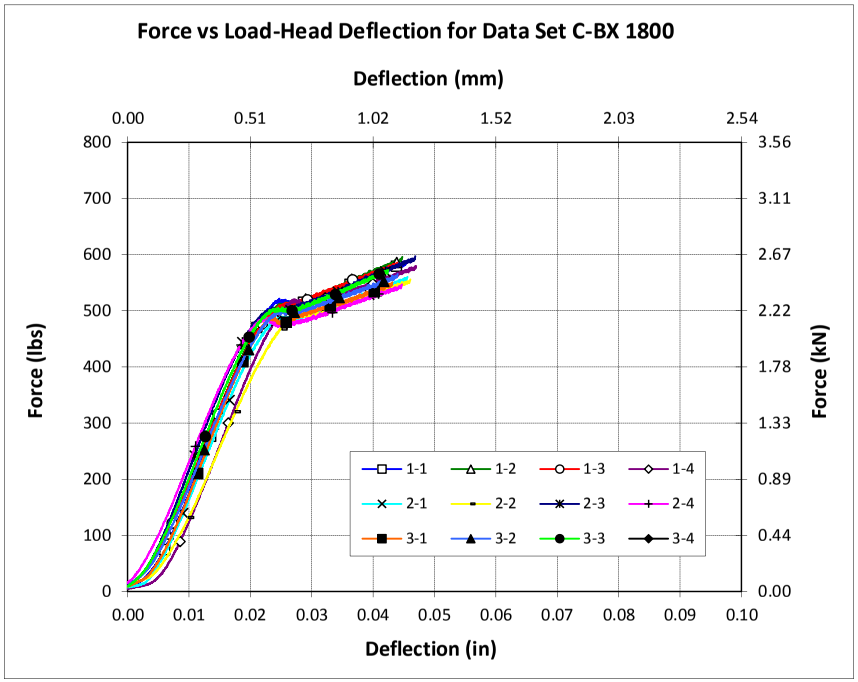




Shear Test Results Summary for the C-BX 1800 Data Set

Notes	Specimen Number	V-Notch Dimensions						Maximum Load				Strength at Max Load				Modulus		0.2% Offset		
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis		Strain	Strength	
	#	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	ksi	MPa	%	ksi	MPa
	1-1	0.3990	10.13	0.1534	3.897	0.0612	39.49	577.9	2.571	585.3	2.604	9.441	65.09	9.562	65.93	**0.5860**	**4.041**	1.240	**6.075**	**41.89**
	1-2	0.3933	9.99	0.1534	3.897	0.0603	38.93	591.9	2.633	595.8	2.650	9.809	67.63	9.875	68.08	**0.4669**	**3.219**	1.575	**6.480**	**44.68**
	1-3	0.3943	10.01	0.1513	3.842	0.0596	38.47	580.7	2.583	585.5	2.604	9.738	67.14	9.818	67.70	**0.5154**	**3.554**	1.370	**6.000**	**41.37**
	1-4	0.3960	10.06	0.1546	3.927	0.0612	39.50	572.3	2.546	579.7	2.579	9.348	64.46	9.470	65.29	**0.5705**	**3.934**	1.246	**6.010**	**41.44**
	2-1	0.4005	10.17	0.1448	3.677	0.0580	37.40	552.8	2.459	560.3	2.493	9.535	65.74	9.666	66.64	**0.5459**	**3.764**	1.334	**6.240**	**43.02**
	2-2	0.3910	9.93	0.1476	3.748	0.0577	37.22	547.2	2.434	555.7	2.472	9.484	65.39	9.632	66.41	**0.5100**	**3.517**	1.460	**6.440**	**44.40**
	2-3	0.3988	10.13	0.1462	3.712	0.0583	37.60	594.7	2.645	597.1	2.656	10.20	70.35	10.25	70.64	**0.5930**	**4.089**	1.300	**6.460**	**44.54**
	2-4	0.3983	10.12	0.1440	3.657	0.0573	36.99	544.4	2.422	547.0	2.433	9.496	65.47	9.540	65.78	**0.5180**	**3.572**	1.390	**6.173**	**42.56**
	3-1	0.3963	10.06	0.1505	3.821	0.0596	38.46	544.4	2.422	550.8	2.450	9.132	62.96	9.239	63.70	**0.5498**	**3.791**	1.401	**6.603**	**45.53**
	3-2	0.3950	10.03	0.1509	3.833	0.0596	38.46	552.8	2.459	565.4	2.515	9.273	63.93	9.484	65.39	**0.4521**	**3.117**	1.563	**6.163**	**42.49**
	3-3	0.3920	9.96	0.1501	3.813	0.0588	37.96	566.7	2.521	572.4	2.546	9.632	66.41	9.728	67.08	**0.4880**	**3.365**	1.576	**6.700**	**46.20**
	3-4	0.3963	10.06	0.1508	3.830	0.0597	38.55	536.0	2.384	568.7	2.529	8.971	61.86	9.517	65.62	**0.4526**	**3.120**	1.760	**7.070**	**48.75**
	MEAN	***0.3959***	***10.06***	***0.1498***	***3.804***	***0.0593***	***38.25***	***563.5***	***2.507***	***572.0***	***2.544***	***9.505***	***65.54***	***9.648***	***66.52***	***0.5207***	***3.590***	***1.435***	***6.368***	***43.91***
	COV	***0.74***	***0.74***	***2.31***	***2.31***	***2.18***	***2.18***	***3.53***	***3.53***	***2.96***	***2.96***	***3.42***	***3.42***	***2.63***	***2.63***	***9.50***	***9.50***	***10.96***	***5.03***	***5.03***





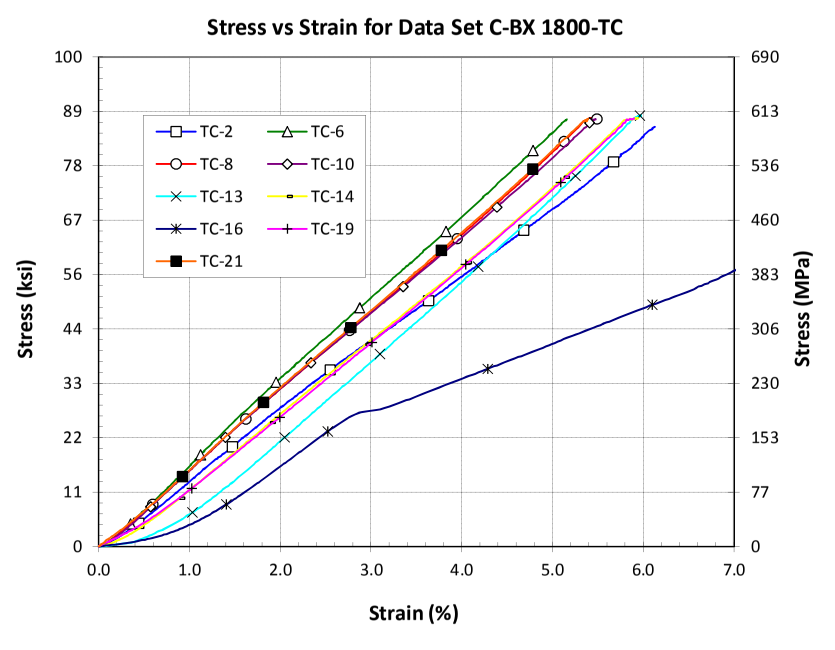
Through-Thickness Compression Test Results Summary for the C-BX 1800 Data Set

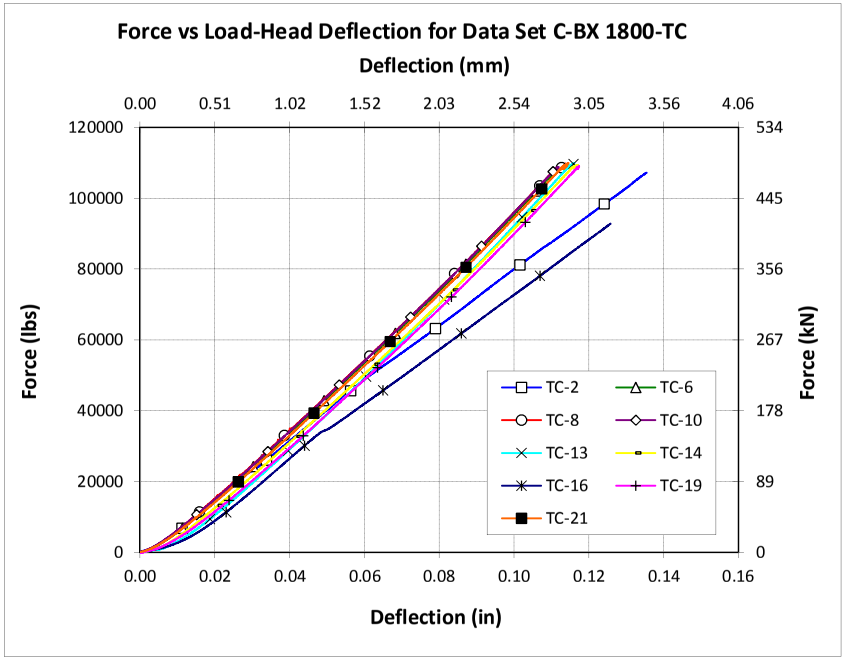
Notes	Specimen Number	Specimen Dimensions						Maximum Load				Strength at Max Load				Modulus		Failure Strain	Poisson's	
		Diameter		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis			ν_{31}	ν_{32}
	#	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%		
1, 3	TC-2	1.260	32.01	0.8956	22.75	1.247	804.7	106,947	475.7	107,222	476.9	85.75	591.2	**85.97**	**592.7**	**0.002**	**0.01**	6.129	0.0575	0.0706
2	TC-6	1.294	32.86	0.8982	22.81	1.314	848.0	108,771	483.8	108,778	483.9	82.75	570.6	**82.76**	**570.6**	**0.002**	**0.01**	5.160		
2	TC-8	1.294	32.87	0.8983	22.82	1.315	848.4	109,771	488.3	109,838	488.6	83.47	575.5	**83.52**	**575.9**	**0.002**	**0.01**	5.516	0.0925	0.0936
1	TC-10	1.293	32.83	0.8983	22.82	1.312	846.5	108,881	484.3	108,840	484.1	82.99	572.2	**82.95**	**571.9**	**0.00**	**0.01**	5.477		
1	TC-13	1.297	32.94	0.8970	22.78	1.321	852.1	109,870	488.7	109,845	488.6	83.19	573.6	**83.17**	**573.5**	**0.002**	**0.01**	5.976	0.0758	0.2519
1	TC-14	1.294	32.87	0.8974	22.79	1.315	848.7	109,156	485.5	109,346	486.4	82.98	572.1	**83.13**	**573.1**	**0.002**	**0.01**	5.944		
2, 3	TC-16	1.247	31.68	0.8964	22.77	1.222	788.4	92,714	412.4	92,819	412.9	75.87	523.1	**75.96**	**523.7**	**0.001**	**0.009**	9.256	0.0655	0.0774
2	TC-19	1.296	32.91	0.9006	22.87	1.319	850.9	109,046	485.1	108,979	484.8	82.68	570.1	**82.63**	**569.7**	**0.001**	**0.010**	5.898		
1	TC-21	1.294	32.87	0.9013	22.89	1.315	848.7	108,936	484.6	109,924	489.0	82.81	571.0	**83.56**	**576.2**	**0.002**	**0.01**	5.391	0.1028	0.1061
	MEAN	***1.288***	***32.71***	***0.8975***	***22.80***	***1.303***	***840.5***	***107,121***	***476.5***	***107,288***	***477.2***	***82.50***	***568.8***	***82.63***	***569.7***	***0.002***	***0.01***	***6.083***	***0.0814***	***0.0837***
	COV	***1.20***	***1.20***	***0.20***	***0.20***	***2.36***	***2.36***	***5.10***	***5.10***	***5.12***	***5.12***	***3.22***	***3.22***	***3.26***	***3.26***	***9.9***	***9.9***	***20.3***	***21.5***	***22.7***

Note 1: The x-axis in Aramis is the 1-direction of the lamina.

Note 2: The x-axis in Aramis is the 2-direction of the lamina.

Note 3: Load mod





Mode-I Fracture Test Summary for the Carbon/ProSet Epoxy Test Specimens

x-diff *mm*
0.035

Δ Slope *%*
5.00%

	Specimen		Nonlinear Onset: Position Change			Nonlinear Onset: Slope Change			Linear Region		Peak Load		Individual Panel Stats		
		ID	x-diff	Position	Load	Δ Slope	Position	Load	Load Range	Stiffness			Load-slp	Stiffness	*Peak Load*
	#	*panel #-sp #*	*mm*	*mm*	*N*	*%*	*mm*	*N*	*N*	*N/mm*	*N*	*lbf*	*mean (COV)*	*mean (COV)*	*mean (COV)*
Spec 1		C-m1-1 1-2	0.035	3.780	54.69	5.00	3.663	53.18	17-34	14.24	98.24	22.10			
Spec 2		C-m1-2 1-17	0.035	3.781	56.00	5.00	3.564	53.00	17-34	14.70	101.2	22.76			
Spec 3		C-m1-3 1a-10	0.035	4.589	71.18	5.00	3.959	62.12	17-34	15.77	109.6	24.65	56.1 (9.3%)	14.9 (5.3%)	103 (5.7%)
Spec 4		C-m1-4 2-8	0.035	4.491	56.54	5.00	4.432	55.80	17-34	13.00	96.53	21.72			
Spec 5		C-m1-5 2a-1	0.035	4.174	50.46	5.00	4.126	49.92	17-34	12.41	96.43	21.69			
Spec 6		C-m1-6 2a-16	0.035	4.075	55.82	5.00	3.976	54.52	17-34	13.81	98.15	22.08	53.4 (5.8%)	13.1 (5.4%)	97 (1%)
Spec 7		C-m1-7 3-11	0.035	4.989	55.78	5.00	4.583	51.41	17-34	11.46	94.57	21.27			
Spec 8		C-m1-8 3a-6	0.035	4.949	51.58	5.00	4.743	49.62	17-34	10.20	95.93	21.58			
Spec 9		C-m1-9 3a-19	0.035	4.205	61.59	5.00	4.018	58.94	17-34	15.05	101.5	22.83	53.3 (9.3%)	12.2 (20.6%)	97.3 (3.8%)
Spec 10		C-m1-10 4-2	0.035	4.422	67.06	5.00	4.198	63.81	17-34	15.52	101.9	22.93			
Spec 11		C-m1-11 4-16	0.035	3.970	53.05	5.00	4.033	53.84	17-34	13.42	96.38	21.68			
Spec 12		C-m1-12 4a-9	0.035	4.923	69.00	5.00	4.338	61.42	17-34	14.03	104.2	23.44	59.7 (8.7%)	14.3 (7.6%)	100.8 (4%)
		Max		4.989	71.18		4.743	63.81	**x-diff Range**	15.77	109.6	24.65			
		Min		3.780	50.46		3.564	49.62	29.0%	10.20	94.57	21.27			
		Mean		**4.362**	**58.56**		**4.136**	**55.63**	**Slope Range**	**13.63**	**99.55**	**22.40**			
		COV		**10.0%**	**11.9%**		**8.4%**	**8.7%**	30.6%	**12.2%**	**4.3%**	**4.3%**			
							Range Start %		30.6%						

Propagation Start *(mm)*	60

Panel ID	Position	Load	Toughness Calculations: ao	a	Δ	b	Toughness (G1): Onset	Prop
panel # - sp #	*mm*	*N*	*mm*		*mm*	*mm*	*J/m²*	*J/m²*
C-m1-1 1-2	3.663	53.18	51.40	49.18	9.217	26.23	190.8	1156
C-m1-2 1-17	3.564	53.00	50.86	48.74	9.724	26.30	184.2	1248
C-m1-3 1a-10	3.959	62.12	50.13	47.76	9.272	26.25	246.3	927.5
C-m1-4 2-8	4.432	55.80	50.10	51.88	9.431	26.05	232.2	966.6
C-m1-5 2a-1	4.126	49.92	50.04	52.67	9.131	26.11	191.5	927.0
C-m1-6 2a-16	3.976	54.52	50.98	50.25	9.352	26.21	208.1	992.1
C-m1-7 3-11	4.583	51.41	50.13	54.19	9.876	26.16	210.9	964.3
C-m1-8 3a-6	4.743	49.62	50.58	55.63	10.24	26.13	205.1	873.3
C-m1-9 3a-19	4.018	58.94	50.22	48.99	9.413	26.12	232.9	957.7
C-m1-10 4-2	4.198	63.81	50.26	48.34	9.168	26.08	267.9	975.8
C-m1-11 4-16	4.033	53.84	49.75	50.76	9.814	26.16	205.5	1157
C-m1-12 4a-9	4.338	61.42	50.60	49.65	9.826	26.13	257.1	1043
Max	4.743	63.81	51.40	55.63	10.24	26.30	267.9	1248
Min	3.564	49.62	49.75	47.76	9.131	26.05	184.2	873.3
Mean	**4.136**	**55.63**	**50.42**	**50.67**	**9.539**	**26.16**	**219.4**	**1016**
COV	**8.4%**	**8.7%**	**0.9%**	**4.8%**	**3.7%**	**0.3%**	**12.5%**	**11.1%**

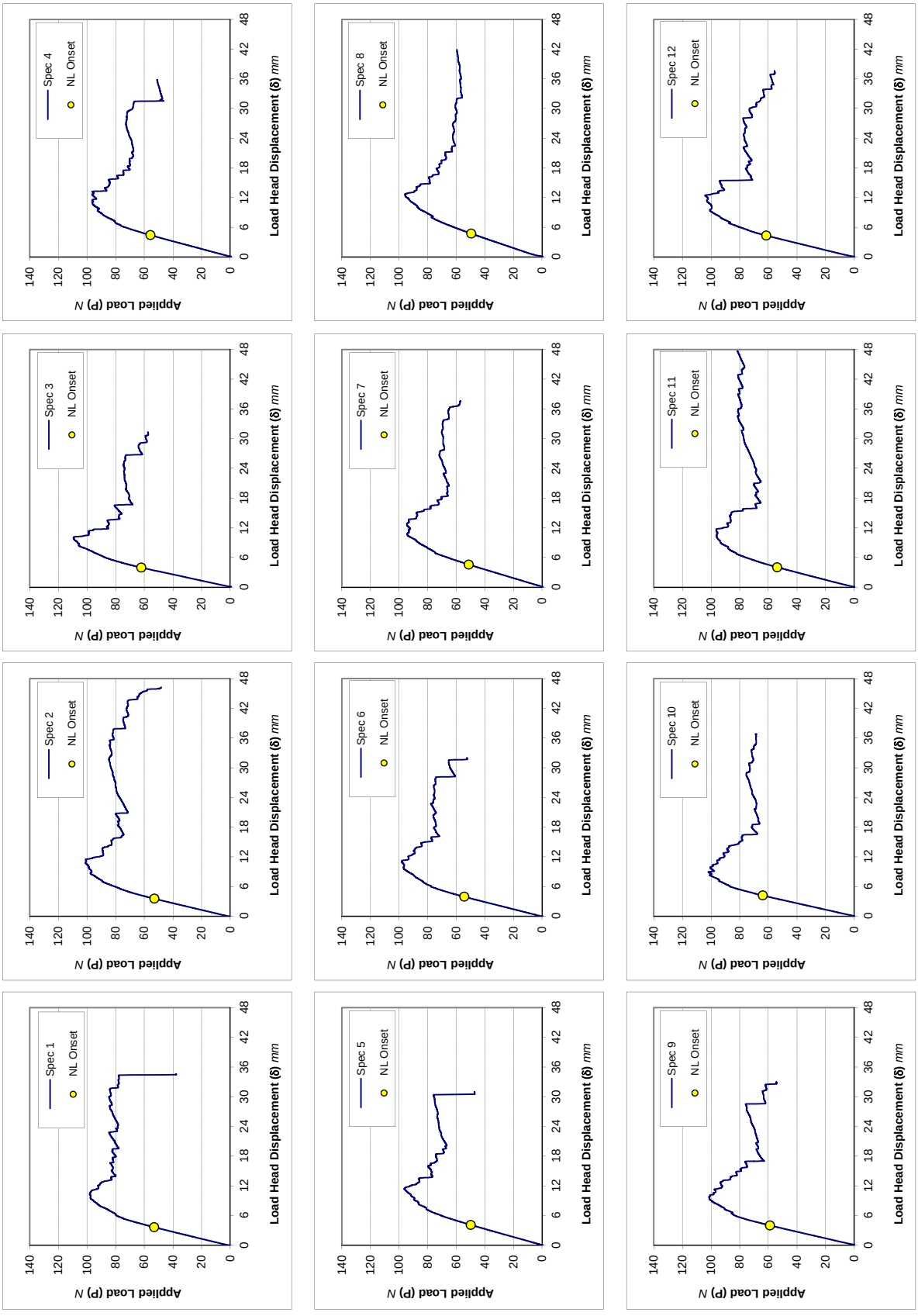
Compliance Calibration Results

Panels 1-4 Compliance

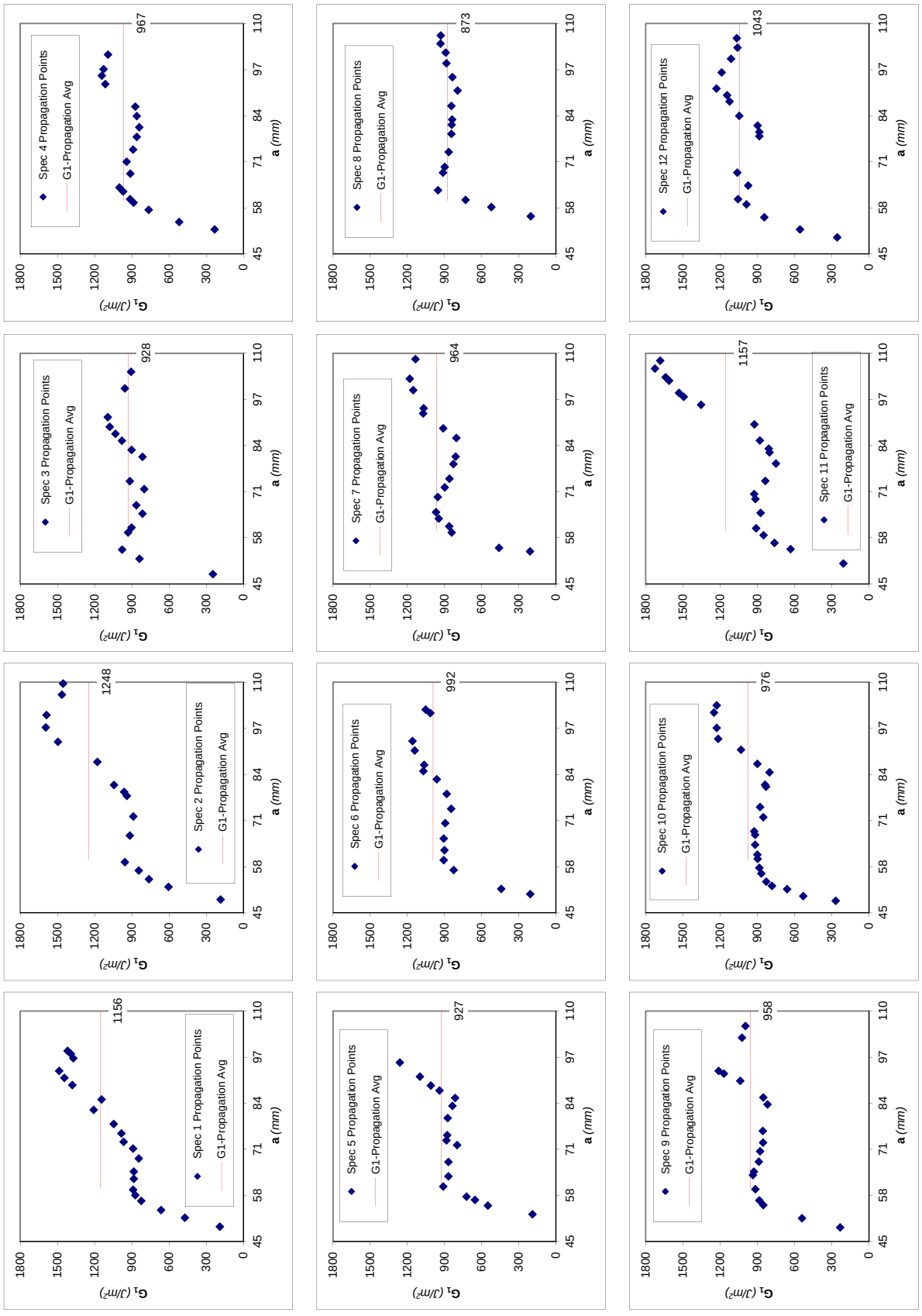
	US	SI
m	2.080E-03	2.176E-06
x	2.6601	
R^2	0.9789	

$$C = m \cdot a^{x} \qquad a = \sqrt[x]{\frac{C}{m}}$$

Load-deflection plots for the Carbon/ProSet Epoxy mode-I fracture toughness test specimens.



Resistance curves (R-curves) for the Carbon/ProSet Epoxy mode-I fracture toughness test specimens.



Mode-II Fracture Toughness Test Summary for the Carbon/ProSet Epoxy Test Specimens

Specimen Dimensions

Specimen ID	SI Units (SI) Width mean	SI Units (SI) Width CV	SI Units (SI) Thickness mean	SI Units (SI) Thickness CV	English Units (US) Width mean	English Units (US) Width CV	English Units (US) Thickness mean	English Units (US) Thickness CV	Initial Crack (a_o) (SI) mean	Initial Crack (a_o) (US) mean
panel # - spec. #	*mm*	*%*	*mm*	*%*	*in*	*%*	*in*	*%*	*mm*	*in*
C-m2-1 1-10	26.17	0.3	5.259	1.2	1.030	0.3	0.2071	1.2	25.4	1.00
C-m2-2 1a-5	26.23	0.4	5.280	3.0	1.033	0.4	0.2079	3.0	25.4	1.00
C-m2-3 1a-18	26.29	0.3	5.206	2.0	1.035	0.3	0.2050	2.0	25.4	1.00
C-m2-4 2-6	26.11	0.6	5.080	1.1	1.028	0.6	0.2000	1.1	25.4	1.00
C-m2-5 2-16	26.12	0.3	4.972	1.4	1.029	0.3	0.1958	1.4	25.4	1.00
C-m2-6 2a-9	26.24	0.4	5.100	2.2	1.033	0.4	0.2008	2.2	25.4	1.00
C-m2-7 3-6	26.01	0.4	5.118	1.5	1.024	0.4	0.2015	1.5	25.4	1.00
C-m2-8 3-19	26.20	0.3	5.080	1.4	1.031	0.3	0.2000	1.4	25.4	1.00
C-m2-9 3a-14	26.22	0.5	5.039	1.4	1.032	0.5	0.1984	1.4	25.4	1.00
C-m2-10 4-9	26.13	0.4	5.024	1.6	1.029	0.4	0.1978	1.6	25.4	1.00
C-m2-11 4a-4	26.17	0.4	5.050	0.8	1.031	0.4	0.1988	0.8	25.4	1.00
C-m2-12 4a-17	26.21	0.5	5.210	1.6	1.032	0.5	0.2051	1.6	25.4	1.00
Mean	**26.18**	**0.3**	**5.118**	**1.9**	**1.031**	**0.3**	**0.2015**	**1.9**	**25.4**	**1.00**

Proposed ASTM Standard

$$C = A + ma^3 \qquad G_Q = \frac{3mP_{Max}^2 a_o^2}{2B}$$

$$\%G_Q = Max\left[\frac{100\left(P_j a_j\right)^2}{\left(P_{Max} a_o\right)^2}\right];\ j = 1, 2$$

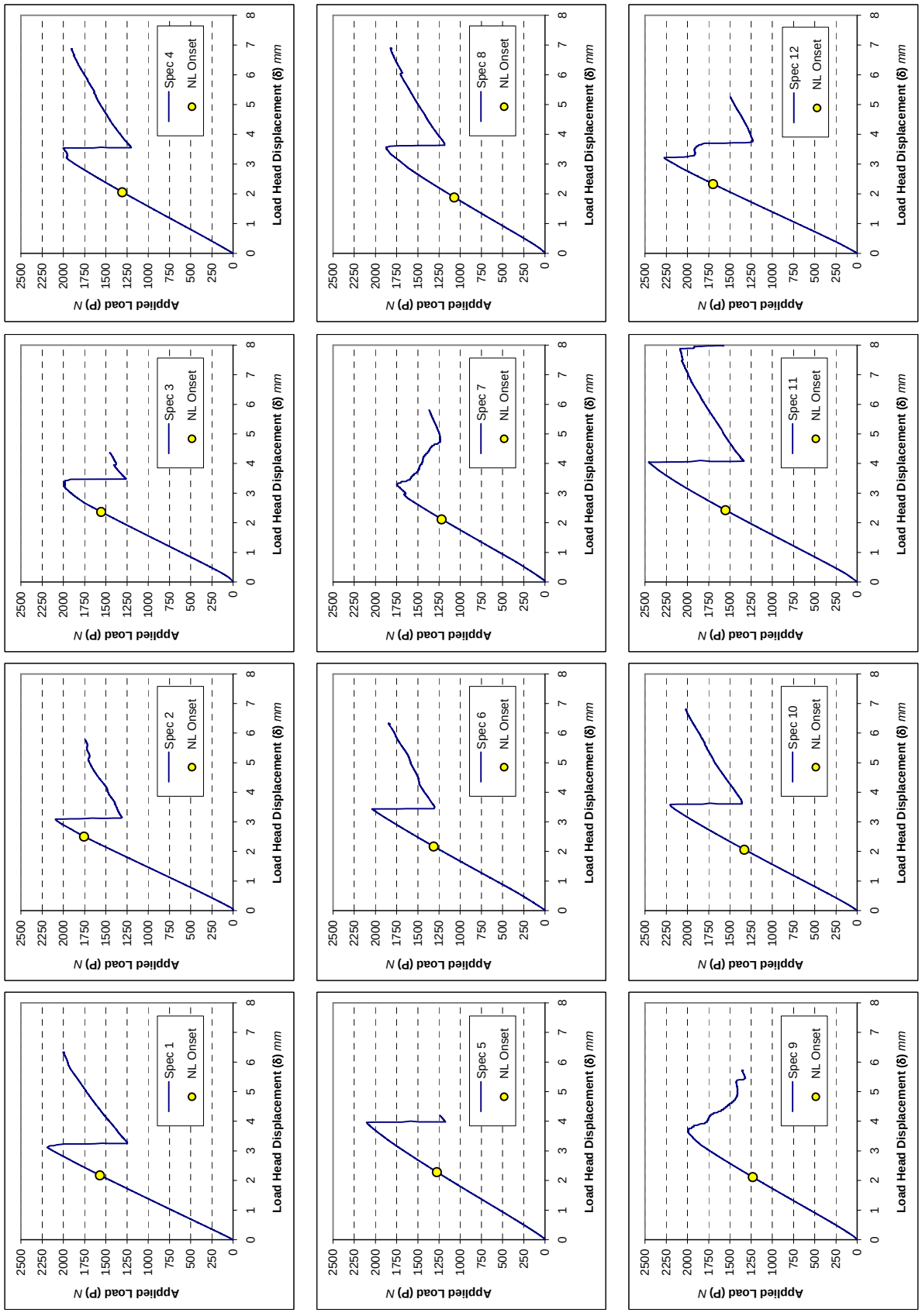
European Standard

$$G_{IIC} = \frac{9 \times P \times a^2 \times d \times 1000}{2 \times w(1/4L^3 + 3a^3)}$$

Toughness Calculations

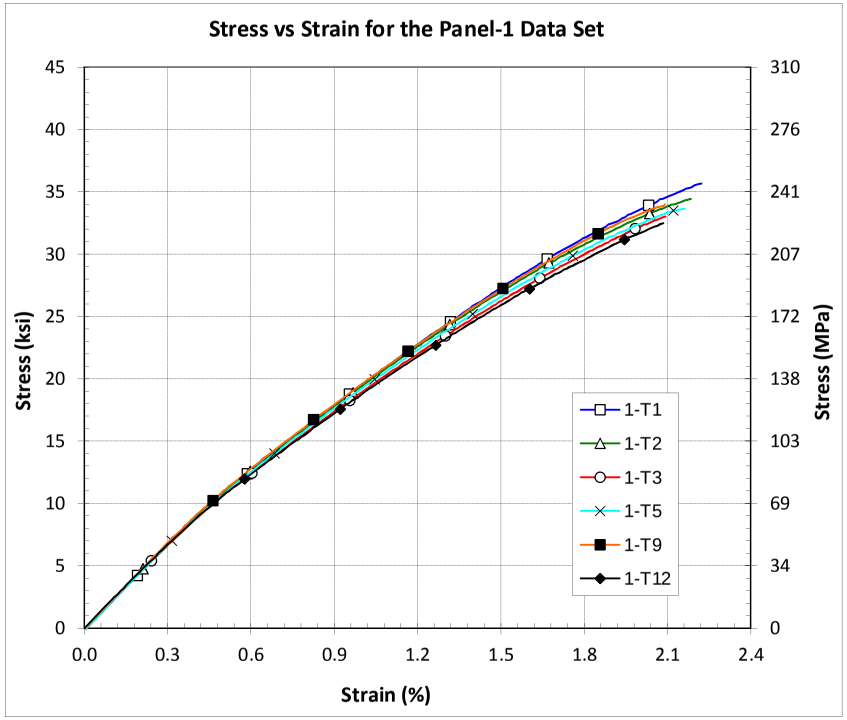
Specimen #	Specimen ID	NL-Onset Load	Max Load (N) a_o	Max Load (N) ao - 8.5	Max Load (N) ao + 8.5	Compliance (mm/N) a_o	Compliance (mm/N) ao - 8.5	Compliance (mm/N) ao + 8.5	%G_Q (%) a_o	%G_Q (%) ao - 8.5	%G_Q (%) ao + 8.5	ASTM Standard: Compliance Cal. m	ASTM Standard: Compliance Cal. R^2	ASTM Standard: Toughness G_{II} NL	ASTM Standard: Panel Stats Mean (CV)	European Standard G_{II} NL
#	*ID*	*N*	a_o	ao - 8.5	ao + 8.5	a_o	ao - 8.5	ao + 8.5	a_o	ao - 8.5	ao + 8.5	*1/Nmm²*		*J/m²*	*J/m² (%)*	*J/m²*
Spec 1	**C-m2-1 1-10**	1567	2190	451.7	456.4	1.368E-03	1.217E-03	1.768E-03	100	3.69	15.1	1.642E-08	0.9948	1491		775.3
Spec 2	**C-m2-2 1a-5**	1754	2095	483.1	449.3	1.388E-03	1.299E-03	1.788E-03	100	3.38	11.7	1.484E-08	0.9720	1684	1571 (6.4)	995.3
Spec 3	**C-m2-3 1a-18**	1554	1993	455.8	451.3	1.450E-03	1.280E-03	1.862E-03	100	3.83	15.0	1.730E-08	0.9972	1537		849.2
Spec 4	**C-m2-4 2-6**	1304	2004	458.9	455.2	1.566E-03	1.364E-03	2.029E-03	100	5.52	21.7	1.971E-08	0.9985	1242		611.5
Spec 5	**C-m2-5 2-16**	1275	2107	480.7	450.5	1.753E-03	1.517E-03	2.287E-03	100	6.33	22.2	2.281E-08	0.9987	1373	1322 (5.3)	662.9
Spec 6	**C-m2-6 2a-9**	1311	2041	530.3	455.5	1.634E-03	1.324E-03	2.061E-03	100	7.28	21.5	2.130E-08	0.9916	1350		644.0
Spec 7	**C-m2-7 3-6**	1217	1752	455.6	457.4	1.694E-03	1.416E-03	2.147E-03	100	6.20	25.0	2.131E-08	0.9979	1175		589.5
Spec 8	**C-m2-8 3-19**	1069	1874	572.5	450.0	1.675E-03	1.364E-03	2.203E-03	100	12.8	31.6	2.453E-08	0.9988	1035	1125 (6.9)	457.6
Spec 9	**C-m2-9 3a-14**	1229	1998	457.3	461.4	1.664E-03	1.444E-03	2.149E-03	100	6.14	25.0	2.088E-08	0.9991	1165		589.9
Spec 10	**C-m2-10 4-9**	1326	2210	579.5	575.5	1.521E-03	1.325E-03	1.953E-03	100	8.44	33.3	1.859E-08	0.9991	1211		623.1
Spec 11	**C-m2-11 4a-4**	1551	2460	466.1	459.3	1.511E-03	1.340E-03	1.959E-03	100	4.01	15.6	1.846E-08	0.9953	1641	1492 (16.3)	856.2
Spec 12	**C-m2-12 4a-17**	1696	2275	501.1	457.0	1.350E-03	1.196E-03	1.711E-03	100	3.88	12.9	1.529E-08	0.9979	1623		898.1
	Mean	**1404**	**2083**	**491.0**	**464.9**	**1.55E-03**	**1.34E-03**	**1.99E-03**	**100.0**	**5.96**	**20.9**	**1.93E-08**	**0.9951**	**1377**		**712.7**
	CV	**15.1%**	**9.0%**	**9.3%**	**7.5%**	**8.9%**	**6.8%**	**9.3%**	**0.0%**	**45.0%**	**33.8%**	**15.6%**	**0.8%**	**15.7%**		**22.3%**

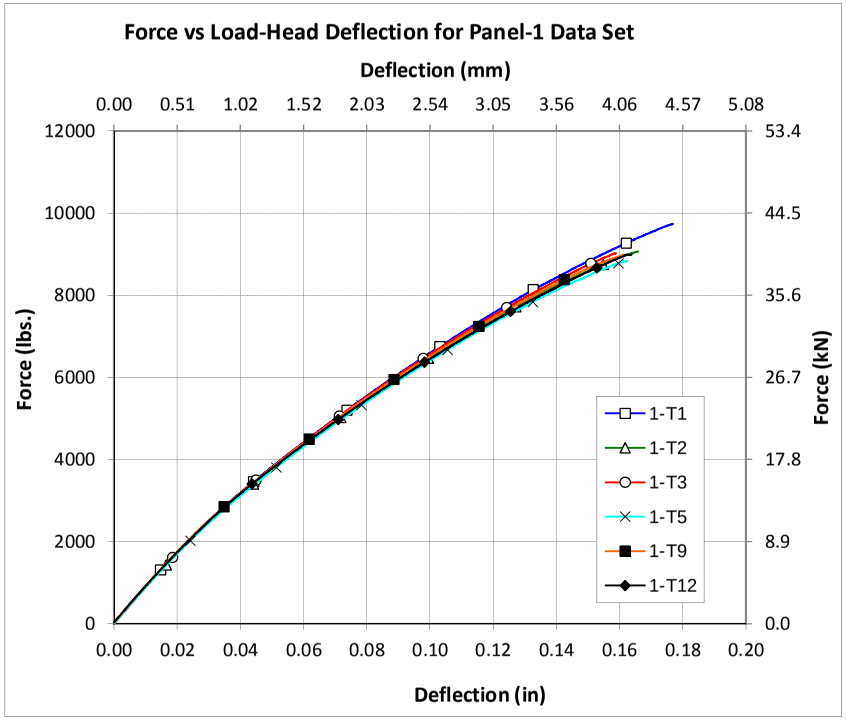
Load-deflection plots for the Carbon/ProSet Epoxy mode-II fracture toughness test specimens



Facesheet Tension Test Results Summary for the Panel-1 Data Set

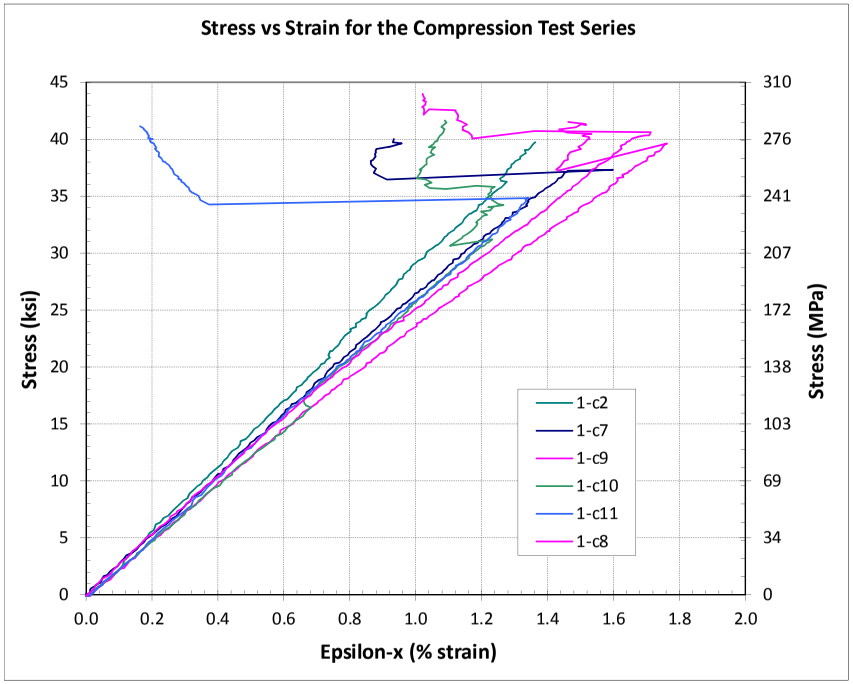
Notes	Specimen Number	Specimen Gage Area Dimensions						Failure Load				Strength				Modulus		Failure		
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis		Strain	Local	Type
	#	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	Gage?	Code
	1-T1	1.006	25.54	0.2690	6.833	0.2705	174.5	9,646	42.91	9,735	43.30	35.66	245.8	35.99	248.1	2.280	15.72	2.22		
	1-T2	0.983	24.96	0.2660	6.756	0.2614	168.6	8,998	40.02	9,066	40.33	34.42	237.3	34.68	239.1	2.261	15.59	2.18		
	1-T3	0.990	25.14	0.2737	6.951	0.2708	174.7	8,943	39.78	9,021	40.13	33.02	227.7	33.31	229.6	2.222	15.32	2.09		
	1-T5	0.980	24.90	0.2657	6.748	0.2604	168.0	8,756	38.95	8,830	39.28	33.62	231.8	33.90	233.8	2.219	15.30	2.16		
	1-T9	0.978	24.85	0.2680	6.807	0.2622	169.2	8,910	39.63	8,984	39.96	33.98	234.3	34.27	236.3	2.247	15.49	2.09		
	1-T12	0.993	25.22	0.2767	7.027	0.2747	177.2	8,921	39.68	8,994	40.01	32.47	223.9	32.74	225.7	2.206	15.21	2.08		
	MEAN	***0.9884***	***25.11***	***0.2721***	***6.912***	***0.2690***	***173.5***	***9,029***	***40.16***	***9,105***	***40.50***	***33.86***	***233.5***	***34.15***	***235.4***	***2.239***	***15.44***	***2.14***		
	COV	***1.3***	***1.3***	***1.7***	***1.7***	***2.2***	***2.2***	***3.5***	***3.5***	***3.5***	***3.5***	***3.3***	***3.3***	***3.3***	***3.3***	***1.3***	***1.3***	***2.7***		

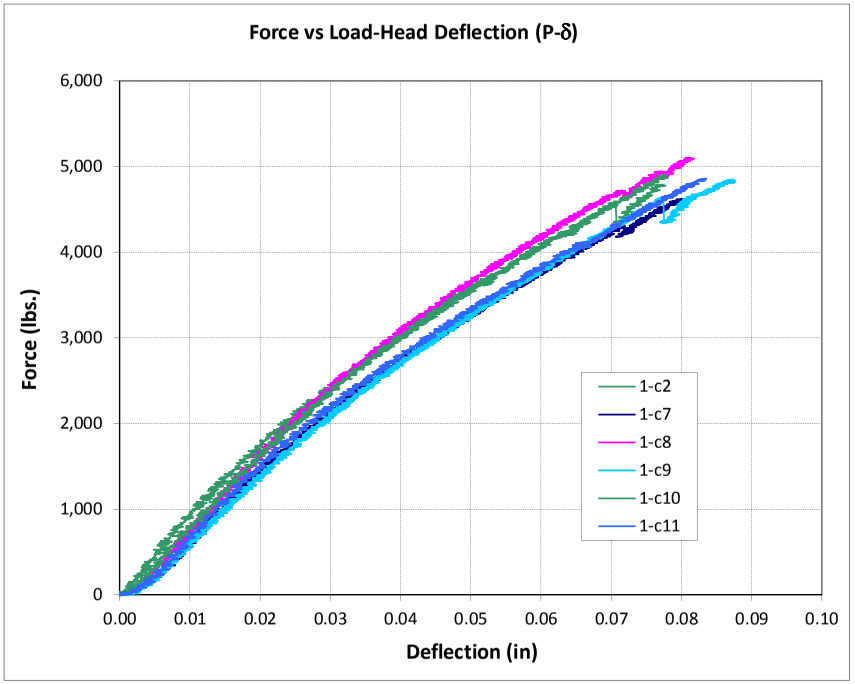




Facesheet Compression Results for Panel Type-1

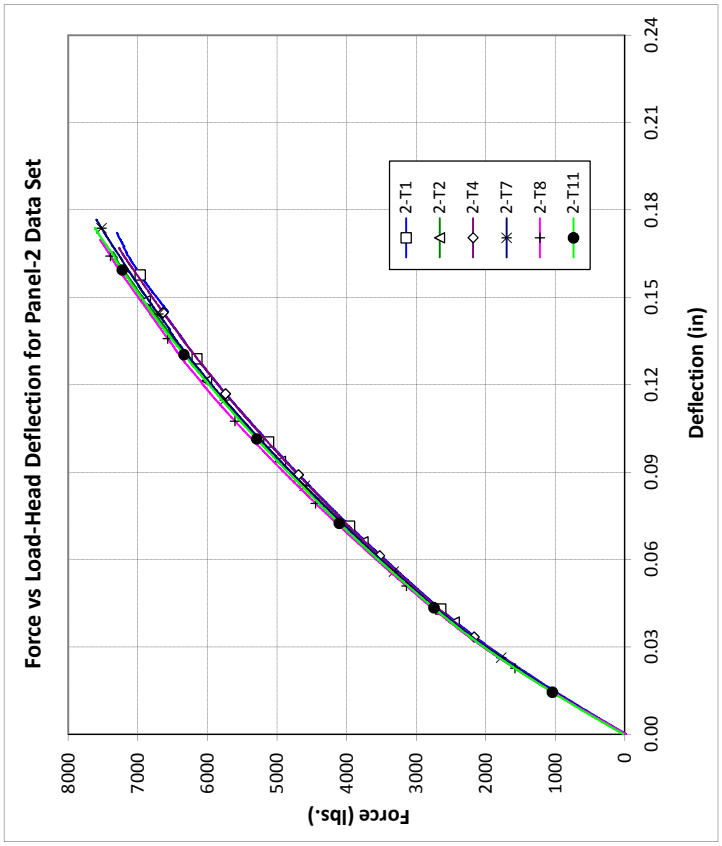
	Specimen Number	Specimen Dimensions						Failure Load				Strength				Modulus		Failure		
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis		Strain	Local	Type
Notes	#	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	Gage?	Code
	1-c2	**0.4903**	12.45	**0.2323**	5.901	**0.1139**	73.50	4,526	20.13	4,793	21.32	39.73	273.9	42.07	290.1	3.025	20.86			
	1-c7	**0.4867**	12.36	**0.2347**	5.961	**0.1142**	73.68	4,570	20.33	4,623	20.56	40.01	275.9	40.48	279.1	2.545	17.55			
	1-c8	**0.4890**	12.42	**0.2350**	5.969	**0.1149**	74.14	5,053	22.48	5,098	22.68	43.97	303.2	44.36	305.9	2.587	17.84			
	1-c9	**0.4927**	12.51	**0.2347**	5.961	**0.1156**	74.59	4,800	21.35	4,851	21.58	41.52	286.3	41.96	289.3	2.573	17.74			
	1-c10	**0.4903**	12.45	**0.2383**	6.054	**0.1169**	75.40	4,866	21.65	4,906	21.82	41.64	287.1	41.98	289.5	2.546	17.56			
	1-c11	**0.4930**	12.52	**0.2367**	6.011	**0.1167**	75.28	4,800	21.35	4,859	21.61	41.14	283.7	41.65	287.1	2.593	17.88			
	MEAN	***0.4943***	***12.55***	***0.2373***	***6.028***	***0.1173***	***75.69***	***4,769***	***21.21***	***4,855***	***21.60***	***41.33***	***285.0***	***42.08***	***290.1***	***2.645***	***18.24***			
	COV	***1.8***	***1.8***	***2.0***	***2.0***	***3.7***	***3.7***	***4.1***	***4.1***	***3.2***	***3.2***	***3.7***	***3.7***	***3.0***	***3.0***	***7.1***	***7.1***			

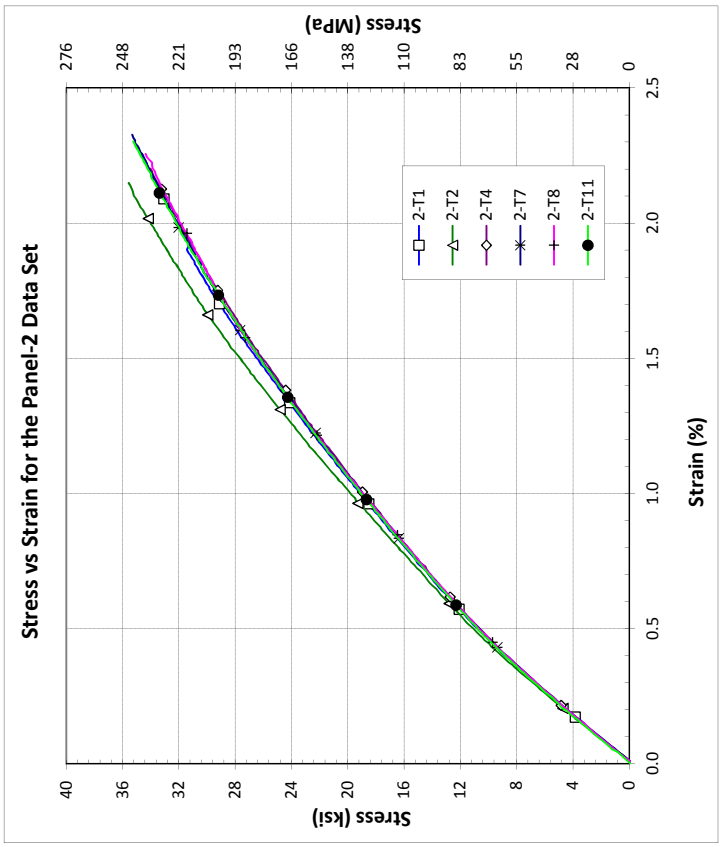




Facesheet Tension Test Results Summary for the Panel-2 Data Set

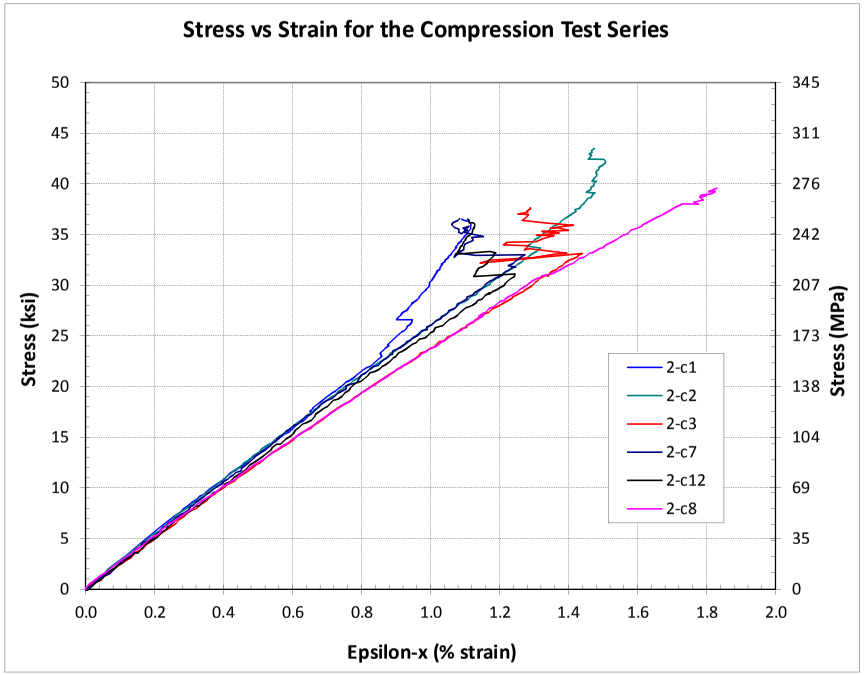
Notes	Specimen Number	Specimen Gage Area Dimensions								Failure Load				Strength				Modulus		Failure	
		Width		Thickness		Area		Aramis			Instron	Aramis			Instron	Aramis		Strain	Local	Type
	#	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	Gage?	Code
	2-T1	0.977	24.82	0.2140	5.436	0.2091	134.9	7,240	32.21	7,300	32.47	34.63	238.8	34.91	240.7	2.291	15.80	2.26		
	2-T2	0.991	25.17	0.2070	5.258	0.2051	132.3	7,295	32.45	7,354	32.71	35.56	245.2	35.85	247.2	2.301	15.87	2.15		
	2-T4	0.983	24.96	0.2153	5.469	0.2116	136.5	7,196	32.01	7,270	32.34	34.01	234.5	34.36	236.9	2.236	15.42	2.20		
	2-T7	0.990	25.15	0.2157	5.478	0.2135	137.7	7,537	33.52	7,595	33.79	35.30	243.4	35.57	245.3	2.243	15.47	2.33		
	2-T8	1.004	25.49	0.2167	5.503	0.2175	140.3	7,471	33.23	7,538	33.53	34.35	236.9	34.66	239.0	2.225	15.34	2.26		
	2-T11	0.987	25.08	0.2170	5.512	0.2143	138.2	7,548	33.57	7,614	33.87	35.23	242.9	35.54	245.0	2.236	15.42	2.30		
	MEAN	*0.9859*	*25.04*	*0.2146*	*5.450*	*0.2116*	*136.5*	*7,381*	*32.83*	*7,445*	*33.12*	*34.85*	*240.3*	*35.15*	*242.3*	*2.255*	*15.55*	*2.25*		
	COV	*1.1*	*1.1*	*1.7*	*1.7*	*1.9*	*1.9*	*2.1*	*2.1*	*2.1*	*2.1*	*1.7*	*1.7*	*1.7*	*1.7*	*1.4*	*1.4*	*2.9*		

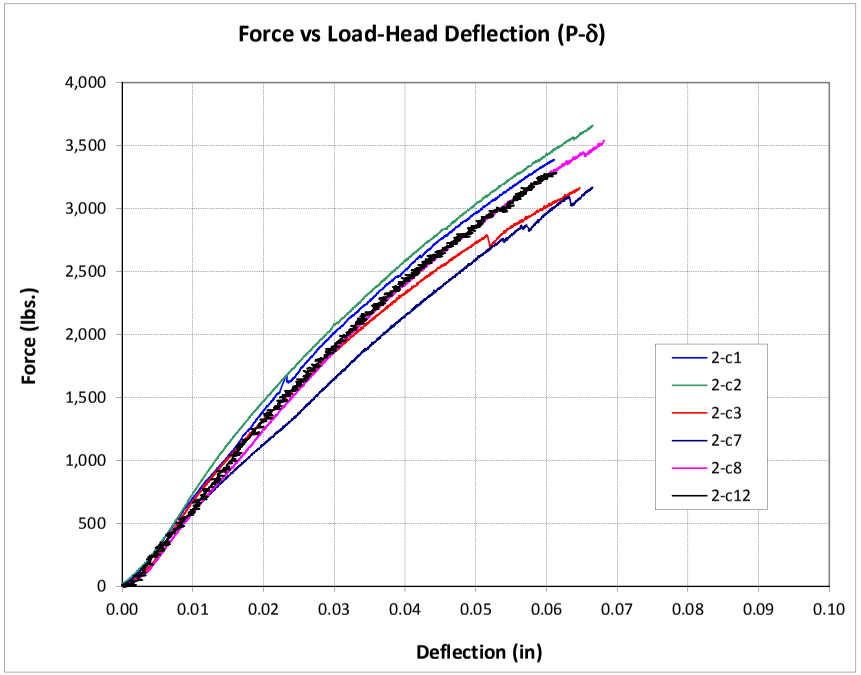




Facesheet Compression Results for Panel Type-2

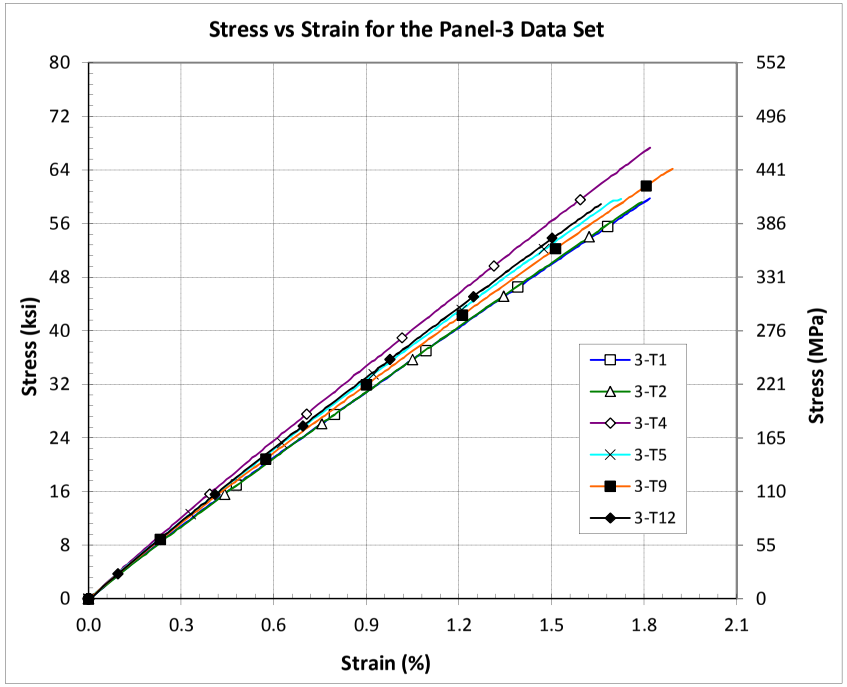
	Specimen Number	Specimen Dimensions						Failure Load				Strength				Modulus		Failure		
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis		Strain	Local	Type
Notes	#	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	Gage?	Code
	2-c1	**0.4870**	12.37	**0.1900**	4.826	**0.0925**	59.70	3,378	15.03	3,388	15.07	**36.51**	251.7	36.61	252.4	2.752	18.98			
	2-c2	**0.4963**	12.61	**0.1690**	4.293	**0.0839**	54.12	3,649	16.23	3,662	16.29	**43.50**	299.9	43.66	301.0	2.681	18.48			
	2-c3	**0.4917**	12.49	**0.1703**	4.326	**0.0837**	54.03	3,152	14.02	3,166	14.08	**37.64**	259.5	37.81	260.7	2.636	18.18			
	2-c7	**0.4917**	12.49	**0.1753**	4.453	**0.0862**	55.62	3,152	14.02	3,169	14.09	**36.56**	252.1	36.76	253.4	2.691	18.55			
	2-c8	**0.5000**	12.70	**0.1770**	4.496	**0.0885**	57.10	3,504	15.59	3,539	15.74	**39.59**	273.0	39.99	275.7	2.496	17.21			
	2-c12	**0.4857**	12.34	**0.1833**	4.657	**0.0890**	57.44	3,252	14.47	3,287	14.62	**36.52**	251.8	36.91	254.5	2.603	17.94			
	MEAN	***0.4928***	***12.52***	***0.1820***	***4.623***	***0.0897***	***57.85***	***3,348***	***14.89***	***3,368***	***14.98***	***38.39***	***264.7***	***38.62***	***266.3***	***2.643***	***18.22***			
	COV	***0.8***	***0.8***	***4.1***	***4.1***	***3.9***	***3.9***	***6.0***	***6.0***	***6.0***	***6.0***	***7.2***	***7.2***	***7.2***	***7.2***	***3.3***	***3.3***			

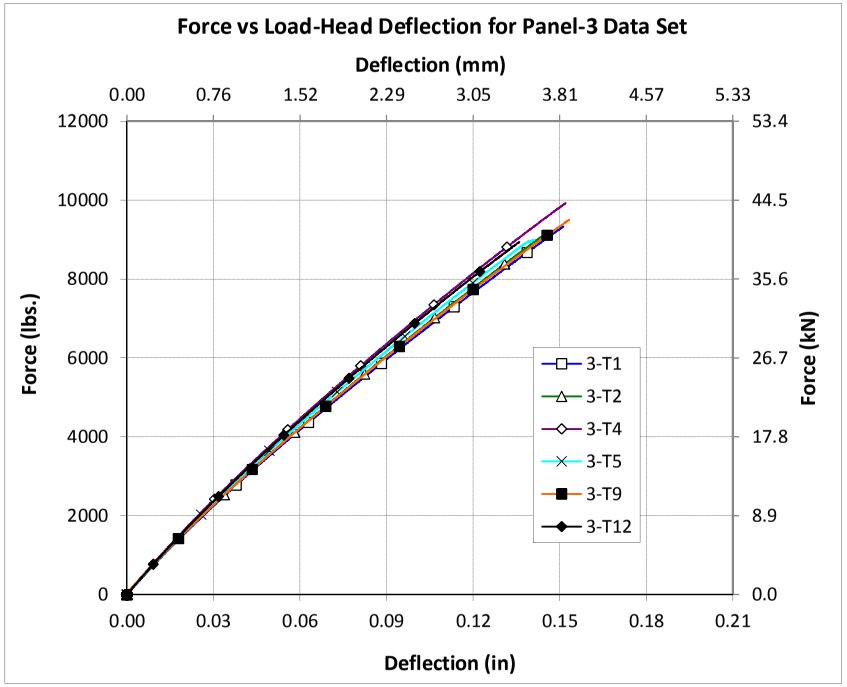




Facesheet Tension Test Results Summary for the Panel-3 Data Set

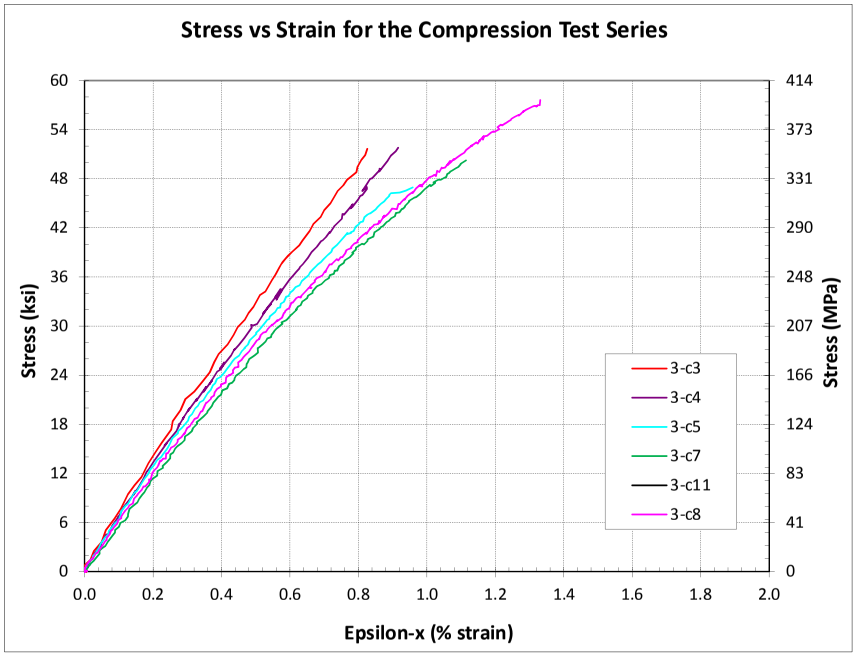
Notes	Specimen Number #	Specimen Gage Area Dimensions: Width in	Width mm	Thickness in	Thickness mm	Area in^2	Area mm^2	Failure Load: Aramis lbs.	Aramis kN	Instron lbs.	Instron kN	Strength: Aramis ksi	Aramis MPa	Instron ksi	Instron MPa	Modulus: Aramis Msi	Aramis GPa	Failure: Strain %	Local Gage?	Type Code
	3-T1	1.011	25.67	0.1530	3.886	0.1546	99.76	9,240	41.10	9,331	41.51	59.75	412.0	60.34	416.0	3.563	24.57	1.82		
	3-T2	1.012	25.71	0.1517	3.852	0.1535	99.06	9,086	40.42	9,166	40.77	59.18	408.0	59.70	411.6	3.518	24.26	1.79		
	3-T4	1.011	25.68	0.1440	3.658	0.1456	93.92	9,800	43.59	9,926	44.15	67.31	464.1	68.18	470.1	4.035	27.82	1.82		
	3-T5	1.006	25.55	0.1487	3.776	0.1496	96.49	8,921	39.68	8,986	39.97	59.65	411.3	60.08	414.2	3.740	25.79	1.73		
	3-T9	1.009	25.62	0.1453	3.691	0.1466	94.58	9,404	41.83	9,502	42.27	64.15	442.3	64.82	446.9	3.682	25.39	1.89		
	3-T12	1.009	25.64	0.1490	3.785	0.1504	97.03	8,855	39.39	8,936	39.75	58.88	406.0	59.42	409.7	3.824	26.36	1.66		
	MEAN	***1.008***	***25.60***	***0.1526***	***3.877***	***0.1538***	***99.23***	***9,218***	***41.00***	***9,308***	***41.40***	***61.49***	***423.9***	***62.09***	***428.1***	***3.727***	***25.70***	***1.78***		
	COV	***0.3***	***0.3***	***4.2***	***4.2***	***4.1***	***4.1***	***3.8***	***3.8***	***4.0***	***4.0***	***5.6***	***5.6***	***5.8***	***5.8***	***5.0***	***5.0***	***4.6***		

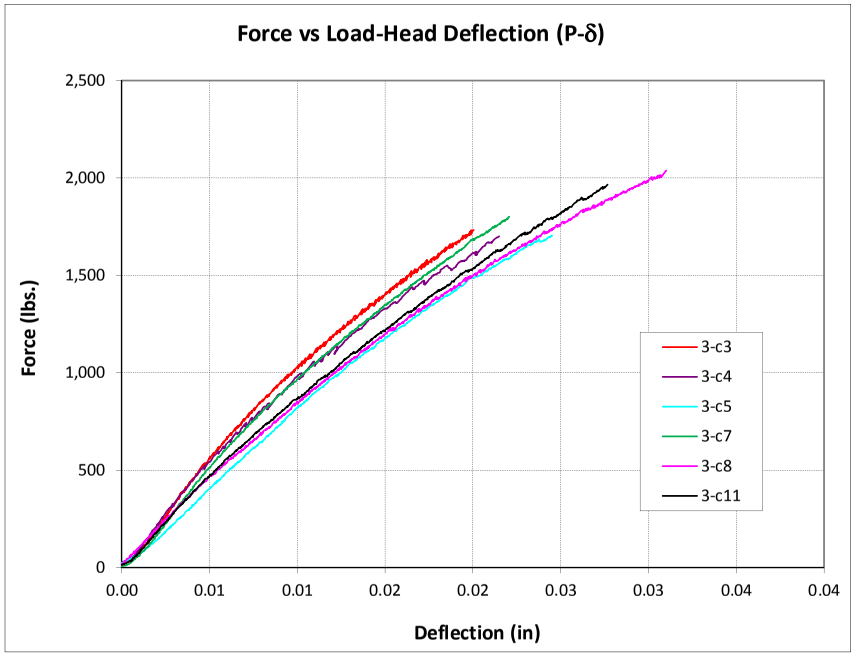




Facesheet Compression Results for Panel Type-3

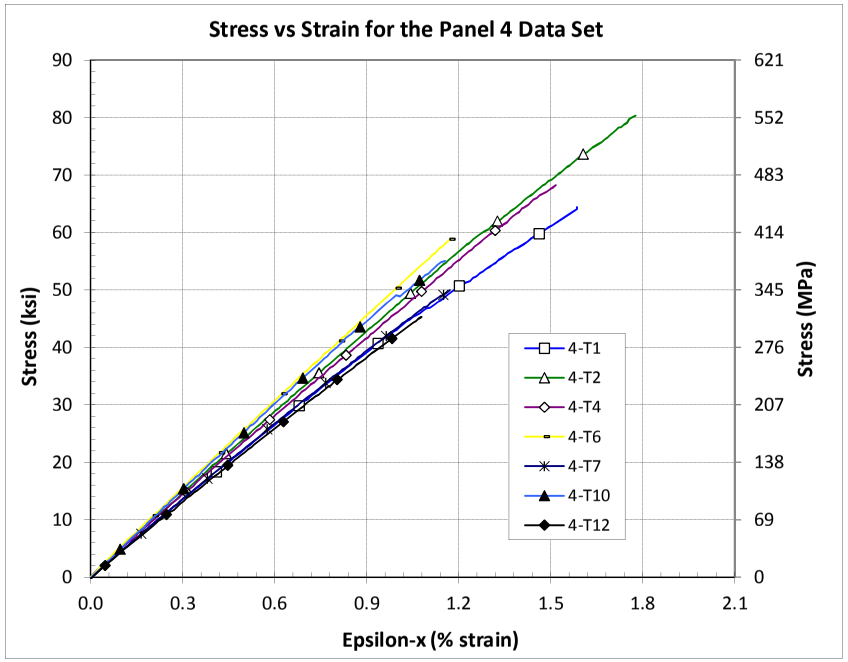
	Specimen Number	Specimen Dimensions						Failure Load				Strength				Modulus		Failure		
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis		Strain	Local	Type
Notes	#	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	Gage?	Code
	3-c3	**0.481**	12.21	**0.069**	1.75	**0.033**	21.4	1,711	7.61	1,733	7.71	**51.66**	356.2	52.32	360.7	6.67	46.0	0.83		
	3-c4	**0.479**	12.17	**0.068**	1.74	**0.033**	21.1	1,697	7.55	1,701	7.56	**51.79**	357.1	51.88	357.7	6.27	43.3	0.92		
	3-c5	**0.479**	12.17	**0.076**	1.92	**0.036**	23.3	1,697	7.55	1,703	7.58	**46.94**	323.6	47.10	324.7	5.99	41.3	0.96		
	3-c7	**0.481**	12.23	**0.074**	1.88	**0.036**	23.0	1,792	7.97	1,801	8.01	**50.24**	346.4	50.48	348.0	5.58	38.5	1.11		
	3-c8	**0.484**	12.30	**0.073**	1.84	**0.035**	22.7	2,027	9.02	2,037	9.06	**57.66**	397.6	57.96	399.6	5.63	38.8	1.33		
	3-c11	**0.481**	12.23	**0.069**	1.76	**0.033**	21.5			1,966	8.74			58.99	406.7					
	MEAN	***0.480***	***12.20***	***0.079***	***2.00***	***0.038***	***24.3***	***1,785***	***7.94***	***1,824***	***8.11***	***51.66***	***356.2***	***53.12***	***366.3***	***6.03***	***41.58***	***1.03***		
	COV	***0.41***	***0.41***	***9.95***	***9.95***	***9.83***	***9.83***	***7.89***	***7.89***	***7.91***	***7.91***	***7.52***	***7.52***	***8.56***	***8.56***	***7.60***	***7.60***	***19.27***		

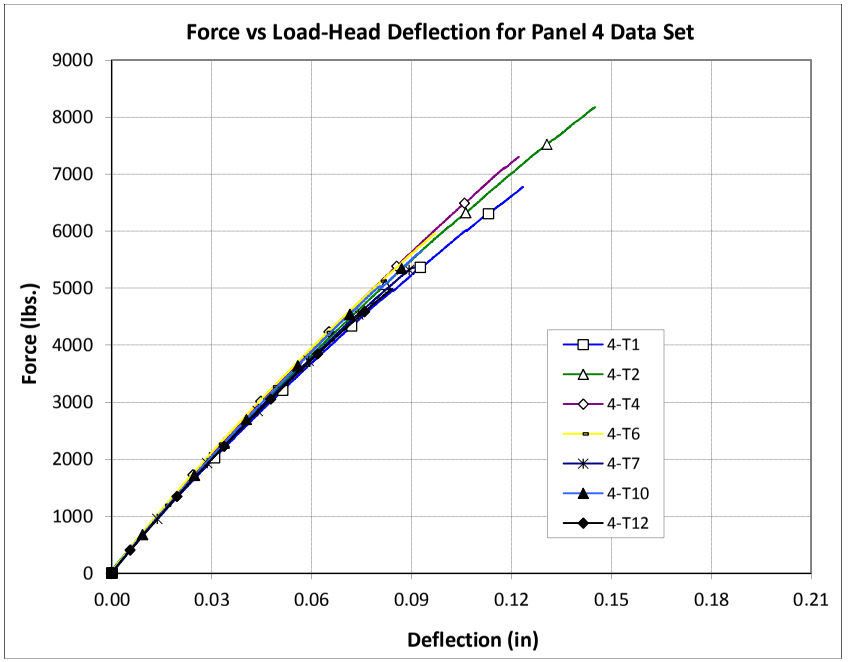




Facesheet Tension Test Results Summary for the Panel 4 Data Set

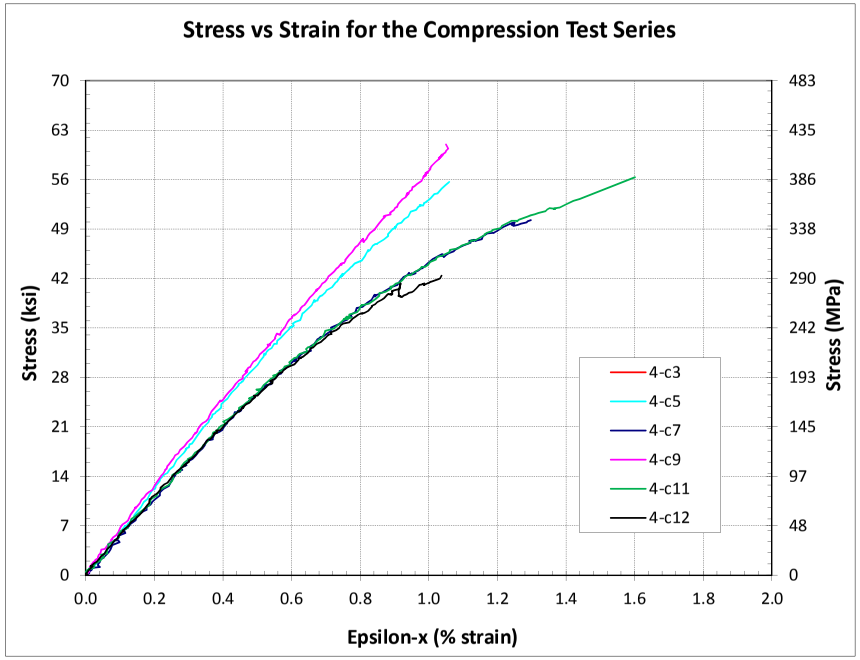
Notes	Specimen Number #	Specimen Gage Area Dimensions: Width in	Width mm	Thickness in	Thickness mm	Area in^2	Area mm^2	Failure Load: Aramis lbs.	Aramis kN	Instron lbs.	Instron kN	Strength: Aramis ksi	Aramis MPa	Instron ksi	Instron MPa	Modulus: Aramis Msi	Aramis GPa	Failure: Strain %	Local Gage?	Type Code
	4-T1	0.9867	25.06	0.1057	2.684	0.1043	67.26	6,713	29.86	6,775	30.14	64.39	443.9	64.98	448.0	4.496	31.00	1.59		
	4-T2	0.9840	24.99	0.1023	2.599	0.1007	64.97	8,086	35.97	8,173	36.36	80.30	553.7	81.17	559.6	4.766	32.86	1.78		
	4-T4	0.9983	25.36	0.1060	2.692	0.1058	68.27	7,218	32.11	7,302	32.48	68.21	470.3	69.00	475.7	4.643	32.02	1.52		
	4-T6	0.9850	25.02	0.1020	2.591	0.1005	64.82	5,911	26.29	5,962	26.52	58.83	405.6	59.34	409.2	5.087	35.07	1.17		
	4-T7	0.9900	25.15	0.1073	2.726	0.1063	68.55	5,306	23.60	5,364	23.86	49.94	344.3	50.48	348.0	4.513	31.11	1.17		
	4-T10	0.9943	25.26	0.1020	2.591	0.1014	65.43	5,581	24.83	5,655	25.15	55.03	379.4	55.76	384.4	5.082	35.04	1.16		
	4-T12	0.9907	25.16	0.1100	2.794	0.1090	70.31	4,933	21.94	4,985	22.17	45.27	312.1	45.74	315.4	4.282	29.52	1.08		
	MEAN	***0.9895***	***25.13***	***0.1066***	***2.707***	***0.1054***	***68.02***	***6,250***	***27.80***	***6,316***	***28.10***	***60.28***	***415.6***	***60.92***	***420.1***	***4.695***	***32.37***	***1.35***		
	COV	***0.5***	***0.5***	***2.9***	***2.9***	***3.1***	***3.1***	***18.1***	***18.1***	***18.1***	***18.1***	***19.7***	***19.7***	***19.7***	***19.7***	***6.5***	***6.5***	***20.1***		

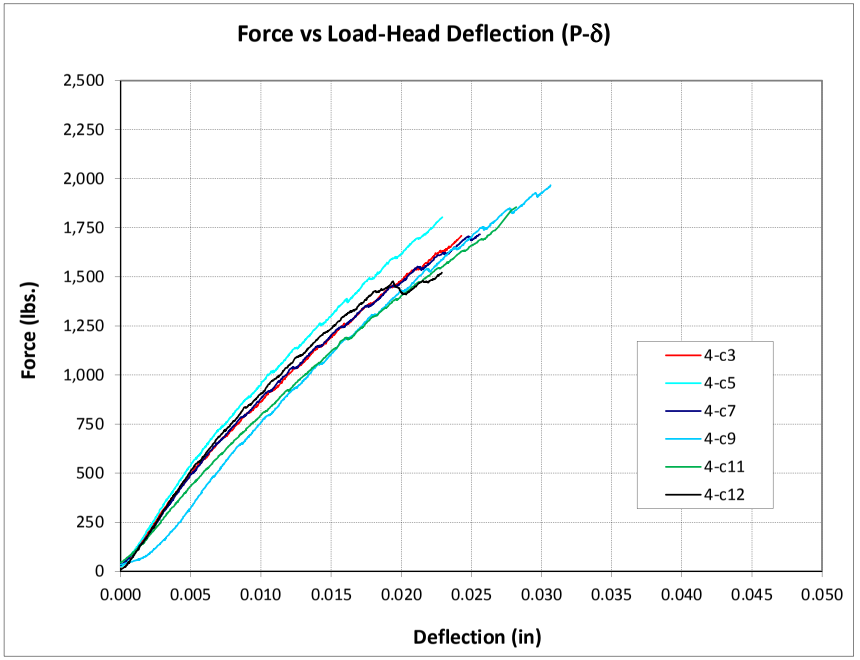




Facesheet Compression Results for Panel Type-4

	Specimen Number	Specimen Dimensions						Failure Load				Strength				Modulus		Failure		
		Width		Thickness		Area		Aramis		Instron		Aramis		Instron		Aramis		Strain	Local	Type
Notes	#	in	mm	in	mm	in^2	mm^2	lbs.	kN	lbs.	kN	ksi	MPa	ksi	MPa	Msi	GPa	%	Gage?	Code
	4-c3	**0.491**	12.47	**0.065**	1.65	**0.032**	20.5			1,709	7.601			53.69	370.2					
	4-c5	**0.498**	12.65	**0.065**	1.65	**0.032**	20.9	1,804	8.02	1,804	8.023	**55.67**	383.9	55.68	383.9	6.12	42.2			
	4-c7	**0.494**	12.56	**0.069**	1.75	**0.034**	22.0	1,714	7.63	1,716	7.635	**50.26**	346.5	50.32	346.9	5.34	36.8			
	4-c9	**0.493**	12.51	**0.066**	1.67	**0.032**	20.9	1,977	8.79	1,967	8.749	**60.97**	420.4	60.67	418.3	6.06	41.8			
	4-c11	**0.492**	12.50	**0.066**	1.68	**0.033**	21.0	1,837	8.17	1,855	8.251	**56.32**	388.3	56.87	392.1	5.06	34.9			
	4-c12	**0.501**	12.72	**0.072**	1.82	**0.036**	23.1	1,519	6.76	1,522	6.769	**42.40**	292.3	42.48	292.9	5.09	35.1			
	MEAN	***0.496***	***12.59***	***0.079***	***2.00***	***0.039***	***25.2***	***1,770***	***7.87***	***1,762***	***7.84***	***53.12***	***366.3***	***53.28***	***367.4***	***5.53***	***38.16***			
	COV	***0.97***	***0.97***	***15.72***	***15.72***	***16.08***	***16.08***	***9.56***	***9.56***	***8.61***	***8.61***	***13.36***	***13.36***	***11.84***	***11.84***	***9.38***	***9.38***			





Appendix G
Finite Element Model Files

G1. Mesh Refinement

Table G1. ***FE Delam Model 06-09-11_Percent_Sizes.txt*** **– Mesh Refinement Impact on SERR**

Run #	Elem Size (% del/2)	No. Elem (ahead / behind)	X_Z / X_S	G_{Imax} (J/m^2)	G_{IImax} (J/m^2)	G_{Tmax} (J/m^2)	G_{II}/G_T	Time (min:sec)
1	5.0	10 / 5	3 / 9	0.642	0.983	1.625	0.605	1:31
2	2.5	10 / 5	3 / 9	2.546	2.447	4.993	0.490	8:57
3	5.0	20 / 10	3 / 9	0.067	0.131	0.198	0.660	5:28
4	2.5	10 / 5	5 / 15	2.267	2.310	4.576	0.505	2:56
5	2.5	10 / 5	3 / 15	2.355	2.434	4.790	0.508	6:32

*Coarse 3D element size is always equal to del_z (fine elem size x X_Z)

Run 1

```
DEL=0.05/2                          ! RELATIVE ELEM SIZE (% OF DELAM SIZE/2)
DEL_X=DEL*L_DEL                     ! FINE ELEMENT SIZE NEAR DELAM FRONT, X-DIR
DEL_Y=DEL*W_DEL                     ! FINE ELEMENT SIZE NEAR DELAM FRONT, Y-DIR
   DEL_Z=3*DEL_Y                    ! 3D ELEMENT SIZE IN Z-DIR (IF DEL_Y < DEL_X)
   DEL_S=9*DEL_Y                    ! COARSE ELEMENT SIZE (IF DEL_Y < DEL_X)
F_MESH=10*DEL               ! FINE MESH EXTENT (# ELEMS X ELEM SIZE)
```

Run 2

```
DEL=0.025/2                         ! RELATIVE ELEM SIZE (% OF DELAM SIZE/2)
DEL_X=DEL*L_DEL                     ! FINE ELEMENT SIZE NEAR DELAM FRONT, X-DIR
DEL_Y=DEL*W_DEL                     ! FINE ELEMENT SIZE NEAR DELAM FRONT, Y-DIR
   DEL_Z=3*DEL_X                    ! 3D ELEMENT SIZE IN Z-DIR (IF DEL_X < DEL_Y)
   DEL_S=9*DEL_X                    ! COARSE ELEMENT SIZE (IF DEL_X < DEL_Y)
F_MESH=10*DEL               ! FINE MESH EXTENT (# ELEMS X ELEM SIZE)
```

Run 3

```
DEL=0.05/2                          ! RELATIVE ELEM SIZE (% OF DELAM SIZE/2)
DEL_X=DEL*L_DEL                     ! FINE ELEMENT SIZE NEAR DELAM FRONT, X-DIR
DEL_Y=DEL*W_DEL                     ! FINE ELEMENT SIZE NEAR DELAM FRONT, Y-DIR
   DEL_Z=3*DEL_X                    ! 3D ELEMENT SIZE IN Z-DIR (IF DEL_X < DEL_Y)
   DEL_S=9*DEL_X                    ! COARSE ELEMENT SIZE (IF DEL_X < DEL_Y)
F_MESH=20*DEL               ! FINE MESH EXTENT (# ELEMS X ELEM SIZE)
```

Run 4

```
DEL=0.025/2                         ! RELATIVE ELEM SIZE (% OF DELAM SIZE/2)
DEL_X=DEL*L_DEL                     ! FINE ELEMENT SIZE NEAR DELAM FRONT, X-DIR
DEL_Y=DEL*W_DEL                     ! FINE ELEMENT SIZE NEAR DELAM FRONT, Y-DIR
   DEL_Z=5*DEL_X                    ! 3D ELEMENT SIZE IN Z-DIR (IF DEL_X < DEL_Y)
   DEL_S=15*DEL_X                   ! COARSE ELEMENT SIZE (IF DEL_X < DEL_Y)
F_MESH=10*DEL               ! FINE MESH EXTENT (# ELEMS X ELEM SIZE)
```

Run 5

```
DEL=0.025/2                         ! RELATIVE ELEM SIZE (% OF DELAM SIZE/2)
DEL_X=DEL*L_DEL                     ! FINE ELEMENT SIZE NEAR DELAM FRONT, X-DIR
DEL_Y=DEL*W_DEL                     ! FINE ELEMENT SIZE NEAR DELAM FRONT, Y-DIR
   DEL_Z=3*DEL_X                    ! 3D ELEMENT SIZE IN Z-DIR (IF DEL_X < DEL_Y)
   DEL_S=15*DEL_X                   ! COARSE ELEMENT SIZE (IF DEL_X < DEL_Y)
F_MESH=10*DEL               ! FINE MESH EXTENT (# ELEMS X ELEM SIZE)
```

1) Set fixed fine/coarse/shell element sizes and extents (Krueger & O'Brien, 2001)
    a. fine 3D: 3 mm/12 elem = 0.25 mm/elem (6 elem each side of front)
    b. coarse 3D: (25–3) mm/8 elem = 2.75 mm/elem (4 elem beyond fine mesh)
    c. shell: ≈4 mm/elem near solids and ≈10 mm/elem farther away

Table G2. *FE Delam Model 06-09-11_Fixed_Sizes.txt* – Mesh Refinement Impact on SERR

Run #	Elem Size (mm)	No. Elem (ahead / behind)	S_Z / S_S (mm)	G_{Imax} (J/m^2)	G_{IImax} (J/m^2)	G_{Tmax} (J/m^2)	G_{II}/G_T	Time (min:sec)
6	0.25	6 / 6	1 / 7	4.301	3.676	7.977	0.461	13:56
7	0.25	6 / 6	1 / 10	4.013	3.525	7.538	0.468	12:08
8	0.25	6 / 6	2 / 7	4.304	3.678	7.982	0.461	12:27
9	0.25	8 / 8	2 / 7	5.010	5.089	10.10	0.504	17:42
10	0.25	6 / 6	2 / 10	4.015	3.581	7.596	0.471	6:36

*Coarse 3D element size is always equal to 2.5 mm (fine elem size x X_Z)

Run 6

```
DEL_F=0.25                    ! FINE ELEMENT SIZE
DEL_C=2.50                    ! COARSE ELEMENT SIZE
DEL_Z=1.00                    ! ELEMENT SIZE IN Z-DIR
DEL_S=7.00                    ! SHELL ELEMENT SIZE
C=3                           ! EXTENT OF FINE REGION AROUND CRACK TIP
```

Run 7

```
DEL_F=0.25                    ! FINE ELEMENT SIZE
DEL_C=2.50                    ! COARSE ELEMENT SIZE
DEL_Z=1.00                    ! ELEMENT SIZE IN Z-DIR
DEL_S=10.0                    ! SHELL ELEMENT SIZE
C=3                           ! EXTENT OF FINE REGION AROUND CRACK TIP
```

Run 8

```
DEL_F=0.25                    ! FINE ELEMENT SIZE
DEL_C=2.50                    ! COARSE ELEMENT SIZE
DEL_Z=2.00                    ! ELEMENT SIZE IN Z-DIR
DEL_S=7.00                    ! SHELL ELEMENT SIZE
C=3                           ! EXTENT OF FINE REGION AROUND CRACK TIP
```

Run 9

```
DEL_F=0.25                    ! FINE ELEMENT SIZE
DEL_C=2.50                    ! COARSE ELEMENT SIZE
DEL_Z=2.00                    ! ELEMENT SIZE IN Z-DIR
DEL_S=7.00                    ! SHELL ELEMENT SIZE
C=4                           ! EXTENT OF FINE REGION AROUND CRACK TIP
```

Run 10

```
DEL_F=0.25                    ! FINE ELEMENT SIZE
DEL_C=2.50                    ! COARSE ELEMENT SIZE
DEL_Z=2.00                    ! ELEMENT SIZE IN Z-DIR
DEL_S=10.0                    ! SHELL ELEMENT SIZE
C=3                           ! EXTENT OF FINE REGION AROUND CRACK TIP
```

2) Add a coarse 3D region outside fine 3D mesh (Krueger & O'Brien, 2001)

Table G3. ***FE Delam Model 06-10-11_Fixed_Coars.txt*** **– Mesh Refinement Impact on SERR**

Run #	Fine 3D Elem (mm)	Coarse 3D Elem (mm)	# Elem (1 Side) (F / C)	G_{Imax} (J/m^2)	G_{IImax} (J/m^2)	G_{Tmax} (J/m^2)	G_{II}/G_T	Time (min:sec)
11	0.25	2.2	6 / 5	0.833	0.632	1.465	0.431	9:40
12	0.25	2.2	8 / 5	0.782	0.624	1.406	0.444	30:01
13	0.25	2.0	6 / 6	0.833	0.632	1.465	0.431	7:32
14	0.25	2.2	6 / 8	0.221	0.186	0.406	0.457	11:57
15	0.50	3.7	3 / 3	0.730	0.646	1.376	0.470	1:45

*Solid element size in Z-dir kept at 2 mm; shell element size kept at 8 mm

Run 11

```
DEL_F=0.25                          ! FINE ELEMENT SIZE
DEL_C=2.20                          ! COARSE ELEMENT SIZE
DEL_Z=2.00                          ! ELEMENT SIZE IN Z-DIR
DEL_S=8.00                          ! SHELL ELEMENT SIZE
C=3                                 ! EXTENT OF FINE REGION AROUND CRACK TIP
D=11                                ! EXTENT OF OUTER COARSE 3D REGION
```

Run 12

```
DEL_F=0.25                          ! FINE ELEMENT SIZE
DEL_C=2.20                          ! COARSE ELEMENT SIZE
DEL_Z=2.00                          ! ELEMENT SIZE IN Z-DIR
DEL_S=8.00                          ! SHELL ELEMENT SIZE
C=4                                 ! EXTENT OF FINE REGION AROUND CRACK TIP
D=11                                ! EXTENT OF OUTER COARSE 3D REGION
```

Run 13

```
DEL_F=0.25                          ! FINE ELEMENT SIZE
DEL_C=2.00                          ! COARSE ELEMENT SIZE
DEL_Z=2.00                          ! ELEMENT SIZE IN Z-DIR
DEL_S=8.00                          ! SHELL ELEMENT SIZE
C=3                                 ! EXTENT OF FINE REGION AROUND CRACK TIP
D=12                                ! EXTENT OF OUTER COARSE 3D REGION
```

Run 14

```
DEL_F=0.25                          ! FINE ELEMENT SIZE
DEL_C=2.20                          ! COARSE ELEMENT SIZE
DEL_Z=2.00                          ! ELEMENT SIZE IN Z-DIR
DEL_S=8.00                          ! SHELL ELEMENT SIZE
C=3                                 ! EXTENT OF FINE REGION AROUND CRACK TIP
D=17.6                        ! EXTENT OF OUTER COARSE 3D REGION
```

Run 15

```
DEL_F=0.50                          ! FINE ELEMENT SIZE
DEL_C=3.67                          ! COARSE ELEMENT SIZE
DEL_Z=2.00                          ! ELEMENT SIZE IN Z-DIR
DEL_S=8.00                          ! SHELL ELEMENT SIZE
C=3                                 ! EXTENT OF FINE REGION AROUND CRACK TIP
D=11                                ! EXTENT OF OUTER COARSE 3D REGION
```

3) Add contact elements at delamination interface (not necessary in Krueger & O'Brien, 2001 – differences are three free edges in ENF specimen and less anticlastic bending effects)

Table G4. ***FE Delam Model 06-10-11_Fixed_Coars_Conta.txt*** **– Delam Size & Depth Impact on SERR**

Run #	Comments	G_{Imax} (J/m^2)	G_{IImax} (J/m^2)	G_{Tmax} (J/m^2)	G_{II}/G_T	Time (min:sec)
16	l_del=51, ld_del=286, d_ply=1	0.000	0.474	0.474	1.000	12:15
17	(16) exc. d_ply=6	0.001	0.452	0.453	0.997	9:24
18	(17) w/1N load abv/blw defect	0.002	0.449	0.451	0.997	11:30
19	(17) exc. ld_del=864	0.000	0.029	0.029	0.998	8:45
20	(17) exc. t_{core}=6, d_ply=5	0.000	6.146	6.146	1.000	14:43
21	(17) exc. t_{core}=3, d_ply=4	0.212	15.85	16.07	0.987	7:28
22	(20) exc. l_del=102, pred,off	0.074	17.35	17.42	0.996	82:00

*Mesh settings constant – del_f=0.3, del_c=3.0, del_z=2.0, del_s=8.0, c=3, d=15

Defect on compression side in shear zone with larger defect (L_DEL=102 mm)
ABORTED – SOLUTION WOULD NOT CONVERGE! (>75 MIN)

Larger defect (L_DEL=102 mm) with t_{core}=6, d_ply=5, pred,off
SOLUTION CONVERGED AT 82 MIN. (Run 22)

Larger defect with t_{core}=6, d_ply=5, pred,on, fkn=0.8, toln=1.2
ABORTED – SOLUTION WOULD NOT CONVERGE! (> 165 MIN)

4) Fixed element coordinate system (ESYS) assignment to match global Cartesian system

Table G5. Shell Mesh Refinement Study

Run #	del_s (mm)	δ_{max} (mm)	σ_{max} (MPa)	G_{IImax} (J/m^2)	Time (min:sec)
X1	20.0	31.30	78.78	1.91	4:00
X2	10.0	31.29	79.01	2.08	5:15
X4	8.0	31.29	79.07	2.08	6:30
X3	5.0	31.30	79.15	2.08	8:24

*d_ply = 5, del_z = 3.0, del_f = 0.4, del_c = 4.0, l_del = 51, t_{core} = 24, xd_del = 286

Table G6. Solid Thru-thickness Mesh Refinement Study

Run #	del_z (mm)	ε_{max} ($x10^{-3}$mm)	σ_{max} (MPa)	G_{IImax} (J/m^2)	Time (min:sec)
X8	8.0	1.96	176	3.81	9:30
X5	5.0	1.96	176	3.84	12:45
X6	3.0	1.96	176	3.86	22:00
X7	1.0	1.96	176	3.87	33:00

*d_ply = 5, del_s = 10.0, del_f = 0.3, del_c = 3.0, l_del = 51, t_{core} = 24, xd_del = 286

Table G7. Systematic Mesh Refinement Study

Run #	del_f (mm)	"C" (mm / #)	del_c (mm)	"D" (mm / #)	G_{IImax} (J/m^2)	G_{II}/G_T (J/m^2)	σ_{max} (MPa)	Time (min:sec)
M1	1.00	8.0 / 8	5.0	20.0 / 4	1.168	0.966	169.4	2:00
M2	0.50	4.0 / 8	5.0	20.0 / 4	1.322	0.967	169.0	5:05
M3	0.25	2.0 / 8	5.0	20.0 / 4	1.382	1.000	168.4	5:43
M4	0.15	1.2 / 8	5.0	20.0 / 4	1.345	1.000	167.3	6:15
M5	0.25	3.0 / 12	5.0	20.0 / 4	1.364	0.974	158.8	15:26
M6	0.25	4.0 / 16	5.0	20.0 / 4	1.338	0.978	169.1	65:57
M7	0.25	1.5 / 6	5.0	20.0 / 4	1.314	1.000	168.1	3:01
M8	0.5	5.0 / $10^{(K)}$	5.0	20.0 / 4	1.197	1.000	169.1	5:43
M9	0.5	5.0 / $10^{(K)}$	$2.5^{(K)}$	12.5 / $5^{(K)}$	3.147	0.886	180.4	17:45
M10	0.5	5.0 / $10^{(K)}$	1.5	7.5 / 5	6.388	0.838	180.6	23:00
M11	0.5	5.0 / $10^{(K)}$	1.0	5.0 / 5	8.681	0.819	182.3	10:08
M12	0.25	3.0 / 12	2.5	15.0 / 6	1.851	1.000	180.5	10:25
M13	0.25	3.0 / 12	1.25	12.5 / 10				

*d_ply = 5, del_z = 5.0, del_s = 10.0, l_del = 51, t_{core} = 24, xd_del = 286

G2. ANSYS Macro Files

The following four *.mac* files are ANSYS macros that need to be in the working directory when executing the input script. The files are also available electronically on the storage media that was provided with the final report.

G2.1. "writeSERR.mac"

```
! Ansys macro to write SERR data
!
! writeSERR,'arg1',arg2,arg3,arg4,arg5,arg6
!
! arg1 - path & name of output file
! arg2 - node number
! arg3 - Mode I SERR
! arg4 - Mode II SERR
! arg5 - total SERR
! arg6 - mixity (GII/Gtotal)
!
*CFOPEN,arg1,txt
*VWRITE,arg2,arg3,arg4,arg5,arg6
(F6.0,'  ',F8.4,'  ',F8.4,'  ',F8.4,'  ',F8.4)
*CFCLOS
!
finish
/eof
```

G2.2. "APPENSERR.mac"

```
! Ansys macro to write SERR data
!
! writeSERR,'arg1',arg2,arg3,arg4,arg5,arg6
!
! arg1 - path & name of output file
! arg2 - node number
! arg3 - Mode I SERR
! arg4 - Mode II SERR
! arg5 - total SERR
! arg6 - mixity (GII/Gtotal)
!
*CFOPEN,arg1,txt,,APPEND
*VWRITE,arg2,arg3,arg4,arg5,arg6
(F6.0,'  ',F8.4,'  ',F8.4,'  ',F8.4,'  ',F8.4)
*CFCLOS
!
finish
/eof
```

G2.3. “HEADERSERR.mac”

```
! Ansys macro to write SERR data
!
! writeSERR,'arg1',arg2,arg3,arg4,arg5,arg6
!
! arg1 - path & name of output file
! arg2 - node number
! arg3 - Mode I SERR
! arg4 - Mode II SERR
! arg5 - total SERR
! arg6 - mixity (GII/Gtotal)
!
*CFOPEN,arg1,txt
*VWRITE,arg2,arg3,arg4,arg5,arg6
(A8,'  ',A8,'  ',A8,'  ',A8,'  ',A8)
*CFCLOS
!
finish
/eof
```

G2.4. “sort2d.mac”

```
! Ansys macro to sort a given numeric array (2d)
!
! sort2d,'arg1',arg2,arg3,arg4
!
! arg1 - Char - Name of the array to sort.
! If not given or if not a character array, the macro does nothing.
! arg2 - Int - First column number by which to sort.
! Defaults to 1 if not given.
! arg3 - Int - Second column number by which to sort.
! Defaults to arg2. Is used if first column has equal cells.
! arg4 - Int - Third column number by which to sort.
! Defaults to arg3. Is used if first & second column has equal cells.
!
! arg5 - Double - Tolerance. Defaults to ZERO.
!
*do,arg6,1,2 ! dummy do loop. exec only once. used for easy exit from macro.
!
! Check for arg1
*get,ar22,parm,'%arg1%',type
*if,ar22,ne,1,exit
!
! get the num rows of the array
*get,ar31,parm,'%arg1%',dim,x
!
! Create a temporary results array for the *moper commands
*del,_zc,,nopr
*dim,_zc,,ar31
!
! check if arg2 is given. if not given assume it is 1.
*if,arg2,le,0,then
arg2=1
*endif
!
```

```
! sort by the first specified column
!
*moper,_zc(1),arg1(1,1),sort,arg1(1,arg2)
!
!
*if,arg3,le,0,exit ! if second column was not specified get out.
!
! re-sort by second specified column IF there are equal cells
! in the first specified column
!
*set,ar28,0 ! temp counter - num rows skipped
!
*do,ar24,1,(ar31-1)
!
*if,ar28,gt,0,then
ar28=ar28-1
*cycle
*endif
!
*if,abs(arg1(ar24,arg2)-arg1(ar24+1,arg2)),gt,arg5,cycle
!
*set,ar29,0 ! temp counter - used for last consec set,last elem addition
*do,ar25,ar24,(ar31-1)
!
! If consecutive cells are the same AND the loop is NOT at the
! last cell, then cycle
ar26=abs(arg1(ar25,arg2)-arg1(ar25+1,arg2)) ! consec cell check
ar27=(ar25-(ar31-1)) ! last cell check
!
*if,ar26,le,arg5,then
*if,ar27,ne,0,cycle
*set,ar29,1
*endif
!
ar28=ar29+(ar25-ar24+1) ! num rows to be sorted
*vlen,ar28
*moper,_zc(1),arg1(ar24,1),sort,arg1(ar24,arg3)
ar28=ar28-1-ar29
*exit
!
*enddo
*enddo
!
!
*if,arg4,le,0,exit ! if third column was not specified get out.
!
! re-sort by third specified column IF there are equal cells
! in the first AND second specified column
!
*set,ar28,0 ! temp counter - num rows skipped
!
*do,ar24,1,(ar31-1)
!
*if,ar28,gt,0,then
ar28=ar28-1
*cycle
*endif
```

```
!
*if,abs(arg1(ar24,arg2)-arg1(ar24+1,arg2)),gt,arg5,cycle
!
*if,abs(arg1(ar24,arg3)-arg1(ar24+1,arg3)),gt,arg5,cycle
!
*set,ar29,0 ! temp counter - used for last consec set,last elem addition
*do,ar25,ar24,(ar31-1)
!
! If consecutive cells are the same AND the loop is NOT at the
! last cell, then cycle
ar26=abs(arg1(ar25,arg2)-arg1(ar25+1,arg2)) ! consec cell (col 1)check
*if,ar26,le,arg5,then
ar26=abs(arg1(ar25,arg3)-arg1(ar25+1,arg3)) ! consec cell (col 2) check
*if,ar26,le,arg5,then
ar27=(ar25-(ar31-1)) ! last cell check
*if,ar27,ne,0,cycle
*set,ar29,1
*endif
*endif
!
ar28=ar29+(ar25-ar24+1) ! num rows to be sorted
*vlen,ar28
*moper,_zc(1),arg1(ar24,1),sort,arg1(ar24,arg3)
ar28=ar28-1-ar29
*exit
!
*enddo
*enddo
!
!
*exit
*enddo
*del,_zc,,nopr

/eof
```

G3. Example ANSYS Input File

Section G3.1 contains a sample of the APDL input file that was created for the ANSYS finite element analysis. The example below is file "FE Delam Model 2BC-1 FCC.txt" and is available in electronic format on the storage media that was provided with the FY09 project final report.

The naming convention for the FE Delam MODEL input file is as follows:

2BC-1 FCC

where:

2 = Sandwich panel type 2
B = Bag side of the panel
C = Defect against the core
1 = One inch defect size
FCC = Applicable to all models - stands for fixed mesh parameters, coarse 3D elements added, and contact elements added.

G3.1 ANSYS Input File "FE Delam Model 2BC-1 FCC.txt"

```
!=============================================================================================!
!                                                                                             !
!                                  ANSYS INPUT FILE                                           !
!                     PANEL DELAMINATION ANLYSIS - SANDWICH                                   !
!                 COMBINED SHELL (4 NODE) - 3D SOLID (8 NODE)                                 !
!                                                                                             !
!=============================================================================================!
!                                                                                             !
!           REQUIRED USER INPUT LINES ARE DENOTED BY <--- AT END OF LINE                      !
!                                                                                             !
!=============================================================================================!

FINISH                                          ! FINISH
/CLEAR                                          ! CLEAR AND START NEW
/PREP7                                          ! ENTER PREPROCESSOR
!/CWD,'C:\Users\Jake\Documents\ANSYS_files'     ! CHANGE WORKING DIRECTORY

! PATH & FILE INFO FOR SERR DATA !

*DIM,FNAME,STRING,32,4
FNAME(1,1)='C:\Users\Jake\Desktop\L2BC1'        ! LEFT EDGE                          <---
FNAME(1,2)='C:\Users\Jake\Desktop\R2BC1'        ! RIGHT EDGE                         <---
FNAME(1,3)='C:\Users\Jake\Desktop\F2BC1'        ! FRONT EDGE                         <---
FNAME(1,4)='C:\Users\Jake\Desktop\B2BC1'        ! BACK EDGE                          <---

!=============================================================================================!
!                            GEOMETRIC CONSTANTS (STARTING VALUES)                            !
!=============================================================================================!

/UNITS,MPA              ! MILLIMETER, NEWTON, MILLIJOULE (N-mm), MPa (N/mm^2)

L_PNL=1727              ! LENGTH OF PANEL (1727=68")                                    <---
W_PNL=432               ! WIDTH OF PANEL (432=17")                                      <---
L_DEL=25                ! LENGTH OF DELAMINATION (102=4")                               <---
W_DEL=25                ! WIDTH OF DELAMINATION (102=4")                                <---
XD_DEL=286              ! X DIST TO CENTER OF DEFECT (286=11.25")                       <---
YD_DEL=216              ! Y DIST TO CENTER OF DEFECT (216=8.5")                         <---
!R_DEL=6                ! DELAM CORNER FILLET RADIUS (6.4=1/4")                         <---
```

```
N_PLY=7                        ! TOTAL # OF PLIES INCLUDING CORE                    <---
*DIM,T_PLY,,N_PLY              ! DIMENSION PLY THICKNESS ARRAY
T_PLY(1)=0.54,1.54,1.54,38     ! THICKNESS OF PLIES 1-4 (MOLD SIDE GOING UP)        <---
T_PLY(5)=1.54,1.54,0.54        ! THICKNESS OF PLIES 5-7                             <---
T_LAM=0                        ! INITIALIZE T_LAM (TOTAL THICKNESS)
*DO,II,1,N_PLY
   T_LAM=T_LAM+T_PLY(II)       ! SUM PLY THICKNESSES
*ENDDO
D_PLY=4                        ! PLY # JUST BELOW DEFECT (MOLD SIDE = PLY 1)        <---
T_DEL=0                        ! INITIALIZE T_DEL (DEPTH OF DEFECT)
*DO,JJ,1,D_PLY
   T_DEL=T_DEL+T_PLY(JJ)       ! DEPTH OF DELAM (FROM MOLD SIDE)
*ENDDO

DEL_F=0.50                     ! FINE ELEMENT SIZE                        ****
DEL_C=2.00                     ! COARSE ELEMENT SIZE                      ****
DEL_Z=5.00                     ! ELEMENT SIZE IN Z-DIR                    ****
DEL_S=10.0                     ! SHELL ELEMENT SIZE                       ****

C=5.0                          ! EXTENT OF FINE REGION AROUND CRACK TIP   ****
LO_MSH=C+L_DEL                 ! OUTER LENGTH DIMEN OF FINE MESH
WO_MSH=C+W_DEL                 ! OUTER WIDTH DIMEN OF FINE MESH
LI_MSH=-C+L_DEL                ! INNER LENGTH DIMEN OF FINE MESH
WI_MSH=-C+W_DEL                ! INNER WIDTH DIMEN OF FINE MESH
D=6.0                          ! EXTENT OF OUTER COARSE 3D REGION         ****

SELTOL,0.01                    ! SET SELECTION TOLERENCE (VS. DEFAULT LOGIC)

! UNIQUE TO 4-POINT BEND CONFIGURATION !

A_SPAN=432                     ! DISTANCE FROM SUPPORT TO LOAD (432=17")            <---
FORCE=-13526                   ! TOTAL LOAD AT EACH LOAD LINE (N)

!=============================================================================================!
!                               SET COORDINATE SYSTEMS                                        !
!=============================================================================================!

LOCAL,11,0                     ! PARALLEL TO GLOBAL - FOR ESYS COMMAND
ESYS,11                        ! ELEM COORD SYS IS CARTESIAN
CSYS,4                         ! SET ACTIVE CS TO WP

!=============================================================================================!
!                                MATERIAL PROPERTIES                                          !
!=============================================================================================!

! DEFINE ALL UNIQUE MATERIAL PROPERTIES !

! E-LTM 1603                                                                          <---

MP,EX,1,24400                  ! X MODULUS (N/mm^2 = MPa)
MP,EY,1,23600                  ! Y MODULUS
MP,EZ,1,11600                  ! Z MODULUS
MP,GXY,1,4120                  ! XY SHEAR MODULUS
MP,GXZ,1,3540                  ! XZ SHEAR MODULUS
MP,GYZ,1,3420                  ! YZ SHEAR MODULUS
MP,PRXY,1,0.15                 ! XY POISSON
MP,PRXZ,1,0.43                 ! XZ POISSON
MP,PRYZ,1,0.44                 ! YZ POISSON

! E-LTCFM 3610                                                                        <---

MP,EX,2,18700                  ! X MODULUS
MP,EY,2,18700                  ! Y MODULUS
```

```
MP,EZ,2,9430                  ! Z MODULUS
MP,GXY,2,2660                 ! XY SHEAR MODULUS
MP,GXZ,2,2760                 ! XZ SHEAR MODULUS
MP,GYZ,2,2680                 ! YZ SHEAR MODULUS
MP,PRXY,2,0.18                ! XY POISSON
MP,PRXZ,2,0.47                ! XZ POISSON
MP,PRYZ,2,0.47                ! YZ POISSON

! H-100 CORE                                                                  <---

MP,EX,3,135                   ! X MODULUS
MP,EY,3,135                   ! Y MODULUS
MP,EZ,3,135                   ! Z MODULUS
MP,GXY,3,35                   ! XY SHEAR MODULUS
MP,GXZ,3,35                   ! XZ SHEAR MODULUS
MP,GYZ,3,35                   ! YZ SHEAR MODULUS
MP,PRXY,3,0.32                ! XY POISON
MP,PRXZ,3,0.32                ! XZ POISON
MP,PRYZ,3,0.32                ! YZ POISON

*DIM,MATL_N,,N_PLY            ! DIMENSION MAT'L # ARRAY
MATL_N(1)=1,2,2,3,2,2,1       ! ENTER MAT'L # FOR EACH PLY                   <---

! CREATE GLOBAL LAMINATE SECTION PROPERTIES !

SECTYPE,1,SHELL,,GLBLPLT                                                     <---
secdata, 0.54, 1, 0.0, 1      ! THICKNESS, MAT ID, ANGLE, NUM INT PTS
secdata, 1.54, 2, 0.0, 1
secdata, 1.54, 2, 0.0, 1
secdata, 38.0, 3, 0.0, 1
secdata, 1.54, 2, 0.0, 1
secdata, 1.54, 2, 0.0, 1
secdata, 0.54, 1, 0.0, 1
secoffset,MID
seccontrol,,,, , , ,

! ENTER MAX STRESS FAILURE CRITERION COMPONENTS !

! E-LTM 1603                                                                 <---

FC,1,S,XTEN,438                    ! N/mm^2 = MPa
FC,1,S,XCMP,-397                   !
FC,1,S,YTEN,404                    !
FC,1,S,YCMP,-390                   !
FC,1,S,ZTEN,30                     !
FC,1,S,ZCMP,-557                   !
FC,1,S,XY,70                       !
FC,1,S,YZ,38                       !
FC,1,S,XZ,38                       !

! E-LTCFM 3610                                                               <---

FC,2,S,XTEN,298                    !
FC,2,S,XCMP,-352                   !
FC,2,S,YTEN,298                    !
FC,2,S,YCMP,-352                   !
FC,2,S,ZTEN,27                     !
FC,2,S,ZCMP,-450                   !
FC,2,S,XY,45                       !
FC,2,S,YZ,32                       !
FC,2,S,XZ,31                       !

! H-100                                                                      <---
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FC,3,S,XTEN,3.5                     !
FC,3,S,XCMP,-2.0                    !
FC,3,S,YTEN,3.5                     !
FC,3,S,YCMP,-2.0                    !
FC,3,S,ZTEN,3.5                     !
FC,3,S,ZCMP,-2.0                    !
FC,3,S,XY,1.6                       !
FC,3,S,YZ,1.6                       !
FC,3,S,XZ,1.6                       !

!=============================================================================!
!                              ELEMENT TYPE DEFINITION                        !
!=============================================================================!

! DEFINE GLOBAL PLATE SHELL ELEMENTS !

ET,1,SHELL181                  ! 4-NODED LAYERED SHELL ELEMENT
KEYOPT,1,1,0                   ! BENDING AND MEMBRANE STIFFNESS
KEYOPT,1,3,2                   ! FULL INTEGRATION WITH INCOMPAT. MODES
KEYOPT,1,4,0                   ! CONSTITUITIVE ALGORITHM (SHELL THICK.)
KEYOPT,1,8,1                   ! STORE DATA FOR TOP & BOT OF ALL LAYERS
KEYOPT,1,9,0                   ! NO USER SUBROUTINE FOR INITIAL THICK.

! DEFINE LOCAL DEFECT REGION SOLID ELEMENTS !

ET,2,SOLID185                  ! 8-NODED STRUCTURAL SOLID ELEMENT
KEYOPT,2,2,2                   ! ENHNCD STRAIN FORM (PRVNT SHEAR LOCKING)
KEYOPT,2,3,0                   ! STRUCTURAL SOLID (NONLAYERED)
KEYOPT,2,6,1                   ! MIXED u-P FORMULATION (0=PURE DISPL. FORM.)

! DEFINE CONTACT ELEMENTS AT DELAM INTERFACE !

ET,3,CONTA178                  ! 3D NODE-TO-NODE CONTACT ELEMENT
KEYOPT,3,1,0                   ! UNIDIRECTIONAL GAP
KEYOPT,3,2,0                   ! AUGMENTED LAGRANGE METHOD
KEYOPT,3,3,0                   ! WEAK SPRING NOT USED
KEYOPT,3,4,1                   ! GAP SIZE BASED ON REAL CONSTANT "GAP"
KEYOPT,3,5,6                   ! CONTACT NORMAL IS IN Z-DIR
KEYOPT,3,7,0                   ! NO TIME/IMPACT CONTROL
KEYOPT,3,9,0                   ! INITIAL GAP IS STEP APPLIED
KEYOPT,3,10,0                  ! STANDARD UNILATERAL CONTACT BEHAVIOR

R,1                            ! DEFINE REAL CONSTANT SET FOR CONTA178
RMOD,1,2,0                     ! SET GAP TO 0
!RMOD,1,1,0.8                  ! FKN (NORMAL STIFFNESS) REDUCITON FACTOR
!RMOD,1,9,1.2                  ! TOLN (PENTRATION TOLER) AMPLIF. FACTOR

!=============================================================================!
!                            DRAW DEFECT REGION                               !
!=============================================================================!

SHIFT=-T_LAM/2                      ! LAMINATE HALF THICKNESS
WPOFFS,,,SHIFT                      ! OFFSET WPLANE TO MOLD SURFACE

X1=XD_DEL-LO_MSH/2                  ! ESTABLISH X-COORD VALUES
X2=XD_DEL-L_DEL/2
X3=XD_DEL-LI_MSH/2
X4=XD_DEL+LI_MSH/2
X5=XD_DEL+L_DEL/2
X6=XD_DEL+LO_MSH/2
Y1=YD_DEL-WO_MSH/2                  ! ESTABLISH Y-COORD VALUES
Y2=YD_DEL-W_DEL/2
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Y3=YD_DEL-WI_MSH/2
Y4=YD_DEL+WI_MSH/2
Y5=YD_DEL+W_DEL/2
Y6=YD_DEL+WO_MSH/2
X0=X1-D                              ! ADD OUTER COARSE REGION X/Y COORDS
X7=X6+D
Y0=Y1-D
Y7=Y6+D
L1=(LO_MSH-L_DEL)/2                  ! ESTABLISH BLOCK LENGTHS
L2=(L_DEL-LI_MSH)/2
W1=(WO_MSH-W_DEL)/2                  ! ESTABLISH BLOCK WIDTHS
W2=(W_DEL-WI_MSH)/2

! CREATE DEFECT REGION VOLUMES !

TMP_N=10001                                 ! VOLUME STARTING NUMBER
*DO,KK,1,N_PLY
   NUMSTR,VOLU,TMP_N                        ! SET VOLUME STARTING NUMBER
   BLC4,X3,Y3,LI_MSH,WI_MSH,T_PLY(KK)       ! DEFINE INNER COARSE MESH VOLUME (1)
   BLC4,X1,Y1,L1,W1,T_PLY(KK)               ! DEFINE FINE MESH VOLUMES (2)
   BLC4,X2,Y1,L2,W1,T_PLY(KK)               ! (3)
   BLC4,X3,Y1,LI_MSH,W1,T_PLY(KK)           ! (4)
   BLC4,X4,Y1,L2,W1,T_PLY(KK)               ! (5)
   BLC4,X5,Y1,L1,W1,T_PLY(KK)               ! (6)
   BLC4,X1,Y2,L1,W2,T_PLY(KK)               ! (7)
   BLC4,X2,Y2,L2,W2,T_PLY(KK)               ! (8)
   BLC4,X3,Y2,LI_MSH,W2,T_PLY(KK)           ! (9)
   BLC4,X4,Y2,L2,W2,T_PLY(KK)               ! (10)
   BLC4,X5,Y2,L1,W2,T_PLY(KK)               ! (11)
   BLC4,X1,Y3,L1,WI_MSH,T_PLY(KK)           ! (12)
   BLC4,X2,Y3,L2,WI_MSH,T_PLY(KK)           ! (13)
   BLC4,X4,Y3,L2,WI_MSH,T_PLY(KK)           ! (14)
   BLC4,X5,Y3,L1,WI_MSH,T_PLY(KK)           ! (15)
   BLC4,X1,Y4,L1,W2,T_PLY(KK)               ! (16)
   BLC4,X2,Y4,L2,W2,T_PLY(KK)               ! (17)
   BLC4,X3,Y4,LI_MSH,W2,T_PLY(KK)           ! (18)
   BLC4,X4,Y4,L2,W2,T_PLY(KK)               ! (19)
   BLC4,X5,Y4,L1,W2,T_PLY(KK)               ! (20)
   BLC4,X1,Y5,L1,W1,T_PLY(KK)               ! (21)
   BLC4,X2,Y5,L2,W1,T_PLY(KK)               ! (22)
   BLC4,X3,Y5,LI_MSH,W1,T_PLY(KK)           ! (23)
   BLC4,X4,Y5,L2,W1,T_PLY(KK)               ! (24)
   BLC4,X5,Y5,L1,W1,T_PLY(KK)               ! (25)
   BLC4,X0,Y0,D,D,T_PLY(KK)                 ! DEFINE OUTER COARSE MESH VOLUMES (26)
   BLC4,X1,Y0,L1,D,T_PLY(KK)                ! (27)
   BLC4,X2,Y0,L2,D,T_PLY(KK)                ! (28)
   BLC4,X3,Y0,LI_MSH,D,T_PLY(KK)            ! (29)
   BLC4,X4,Y0,L2,D,T_PLY(KK)                ! (30)
   BLC4,X5,Y0,L1,D,T_PLY(KK)                ! (31)
   BLC4,X6,Y0,D,D,T_PLY(KK)                 ! (32)
   BLC4,X0,Y1,D,W1,T_PLY(KK)                ! (33)
   BLC4,X6,Y1,D,W1,T_PLY(KK)                ! (34)
   BLC4,X0,Y2,D,W2,T_PLY(KK)                ! (35)
   BLC4,X6,Y2,D,W2,T_PLY(KK)                ! (36)
   BLC4,X0,Y3,D,WI_MSH,T_PLY(KK)            ! (37)
   BLC4,X6,Y3,D,WI_MSH,T_PLY(KK)            ! (38)
   BLC4,X0,Y4,D,W2,T_PLY(KK)                ! (39)
   BLC4,X6,Y4,D,W2,T_PLY(KK)                ! (40)
   BLC4,X0,Y5,D,W1,T_PLY(KK)                ! (41)
   BLC4,X6,Y5,D,W1,T_PLY(KK)                ! (42)
   BLC4,X0,Y6,D,D,T_PLY(KK)                 ! (43)
   BLC4,X1,Y6,L1,D,T_PLY(KK)                ! (44)
   BLC4,X2,Y6,L2,D,T_PLY(KK)                ! (45)
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   BLC4,X3,Y6,LI_MSH,D,T_PLY(KK)          ! (46)
   BLC4,X4,Y6,L2,D,T_PLY(KK)              ! (47)
   BLC4,X5,Y6,L1,D,T_PLY(KK)              ! (48)
   BLC4,X6,Y6,D,D,T_PLY(KK)               ! (49)
   WPOFFS,,,T_PLY(KK)                     ! OFFSET WPLANE TO NEXT PLY
   TMP_N=TMP_N+10000                      ! INCREMENT VOLUME STARTING NUMBER
*ENDDO
VPLOT,ALL                                 ! PLOT ALL VOLUMES

!=============================================================================================!
!                                GLUE VOLUMES                                                 !
!        MAINTAINS CONTINUITY AND REMOVES DUPLICATE NODES ON AREA BOUNDARIES                  !
!=============================================================================================!

CSYS,0                          ! MOVE THE WPLANE BACK TO GLOBAL ORIGIN
WPAVE,0,0,0
CSYS,4

!/TYPE,1,5                      ! CAPPED HIDDEN VIEW TO PREVIEW VOL #s
!/CPLANE,0                      ! CUTTING PLANE NORMAL TO VIEW
!/FOCUS,1,,,-0.5,1              ! MOVE THE CUTTING PLANE IN THE Z-DIR
!/REPLOT                        ! REPLOT WITH NEW FOCAL POINT
!/TYPE,1,6                      ! RETURN TO Z-BUFFERED VIEW

! GLUE VOLUMES WITHIN SAME PLY !

TMP_N=12001                           ! VOLUME STARTING NUMBER
TMP_B=SHIFT                           ! Z COORD OF BOT OF CURRENT PLY
*DO,LL,1,N_PLY
   TMP_T=TMP_B+T_PLY(LL)              ! Z COORD OF TOP OF CURRENT PLY
   NUMSTR,VOLU,TMP_N                  ! SET VOLUME STARTING NUMBER
   VSEL,S,LOC,Z,TMP_B,TMP_T           ! SELECT VOLUMES IN ADJACENT PLIES
   VGLUE,ALL                          ! GLUE SELECTED VOLUMES
   TMP_B=TMP_B+T_PLY(LL)              ! INDEX TO BOT OF NEXT PLY
   TMP_N=TMP_N+10000                  ! INCREMENT VOLUME STARTING NUMBER
*ENDDO

! GLUE VOLS OF ADJACENT PLIES BUT NOT AT DELAM INTERFACE!

TMP_N=15001                           ! VOLUME STARTING NUMBER
TMP_B=SHIFT                           ! Z COORD OF BOT OF CURRENT PLY
*DO,MM,1,N_PLY-1
   TMP_T=TMP_B+T_PLY(MM)+T_PLY(MM+1)! Z COORD OF TOP OF NEXT PLY
   NUMSTR,VOLU,TMP_N                  ! SET VOLUME STARTING NUMBER
   *IF,MM,NE,D_PLY,THEN               ! CHECK IF AT LOCATION OF DELAM
      VSEL,S,LOC,Z,TMP_B,TMP_T        ! SELECT VOLUMES IN ADJACENT PLIES
      VGLUE,ALL                       ! GLUE SELECTED VOLUMES
   *ENDIF
   TMP_B=TMP_B+T_PLY(MM)              ! INDEX TO BOT OF NEXT PLY
   TMP_N=TMP_N+10000                  ! INCREMENT VOLUME STARTING NUMBER
*ENDDO

! GLUE VOLS OF ADJACENT PLIES AROUND THE DELAM !

VSEL,S,LOC,X,X0,X2                                ! LEFT EDGE
VSEL,A,LOC,X,X5,X7                                ! RIGHT EDGE
VSEL,A,LOC,Y,Y0,Y2                                ! FRONT EDGE
VSEL,A,LOC,Y,Y5,Y7                                ! BACK EDGE
Z1=SHIFT+T_DEL                                    ! Z-COORD OF DELAM
VSEL,R,LOC,Z,Z1-T_PLY(D_PLY),Z1+T_PLY(D_PLY+1)    ! SELECT ABOVE/BELOW DELAM
TMP_N=(D_PLY+1)*10000+7000                        ! VOLUME STARTING NUMBER
NUMSTR,VOLU,TMP_N                                 ! SET VOLUME STARTING NUMBER
VGLUE,ALL                                         ! GLUE SELECTED VOLUMES
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! GLUE KPs (AND LINES) AROUND DELAM PERIMETER !

KSEL,S,LOC,Z,Z1                     ! SELECT KPs AT LEFT EDGE
KSEL,R,LOC,X,X2
KSEL,R,LOC,Y,Y2,Y5
NUMMRG,KP,0.001                     ! MERGE KPs

KSEL,S,LOC,Z,Z1                     ! SELECT KPs AT RIGHT EDGE
KSEL,R,LOC,X,X5
KSEL,R,LOC,Y,Y2,Y5
NUMMRG,KP,0.001                     ! MERGE KPs

KSEL,S,LOC,Z,Z1                     ! SELECT KPs AT FRONT EDGE
KSEL,R,LOC,Y,Y2
KSEL,R,LOC,X,X2,X5
NUMMRG,KP,0.001                     ! MERGE KPs

KSEL,S,LOC,Z,Z1                     ! SELECT KPs AT BACK EDGE
KSEL,R,LOC,Y,Y5
KSEL,R,LOC,X,X2,X5
NUMMRG,KP,0.001                     ! MERGE KPs

! SPLIT VOLUMES ALONG LAMINATE MIDPLANE IF NECESSARY !

TMP_B=SHIFT                             ! Z COORD OF BOT OF CURRENT PLY
*DO,NN,1,N_PLY
   TMP_T=TMP_B+T_PLY(NN)                ! Z COORD OF TOP OF CURRENT PLY
   *IF,TMP_T,GT,-0.001,AND,TMP_T,LT,0.001,THEN
      *EXIT                             ! INTERF. AT MIDPLANE - NO NEED TO SPLIT
   *ELSEIF,TMP_T,GT,0,THEN              ! CHECK IF CURRENT VOLUME STRADLES MIDPLANE
      NUMSTR,AREA,10000                 ! SET AREA STARTING NUMBER
      BLC5,XD_DEL,YD_DEL,LO_MSH+2*D+1,WO_MSH+2*D+1    ! CREATE (TEMP) AREA AT MIDPLANE
      VSEL,S,LOC,Z,TMP_B,TMP_T          ! SELECT VOLUMES IF AT MIDPLANE
      VSBA,ALL,10000,,DELETE,DELETE     ! SPLIT SELECTED VOLUMES (SHARE AREAS)
      *EXIT                             ! EXIT AFTER FIRST INSTANCE
   *ENDIF
   TMP_B=TMP_B+T_PLY(NN)                ! INDEX TO BOT OF NEXT PLY
*ENDDO
NUMCMP,ALL                              ! COMPRESS ALL ITEM NUMBERS

!=============================================================================!
!                        DRAW GLOBAL PLATE AREA                               !
!=============================================================================!

CSYS,0                              ! MOVE THE WPLANE BACK TO GLOBAL ORIGIN
WPAVE,0,0,0
CSYS,4

*GET,K_NUM,KP,0,NUM,MAXD            ! GET MAX KP NUMBER
NUMSTR,KP,K_NUM+1                   ! SET KP START NUMBER
*GET,L_NUM,LINE,0,NUM,MAXD          ! GET MAX LINE NUMBER
NUMSTR,LINE,L_NUM+1                 ! SET LINE START NUMBER
*GET,A_NUM,AREA,0,NUM,MAXD          ! GET MAX AREA NUMBER
NUMSTR,AREA,A_NUM+1                 ! SET AREA START NUMBER

K,K_NUM+1,0,0,                      ! FRONT LEFT CORNER KP
K,K_NUM+2,0,W_PNL,                  ! BACK LEFT CORNER KP
K,K_NUM+3,L_PNL,W_PNL,              ! BACK RIGHT CORNER KP
K,K_NUM+4,L_PNL,0,                  ! FRONT RIGHT CORNER KP
L,K_NUM+1,K_NUM+2                   ! LEFT EDGE OF PLATE
L,K_NUM+2,K_NUM+3                   ! BACK EDGE OF PLATE
L,K_NUM+3,K_NUM+4                   ! RIGHT EDGE OF PLATE
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L,K_NUM+4,K_NUM+1                    ! FRONT EDGE OF PLATE

LSEL,S,LOC,X,X0                      ! SELECT LEFT EDGE OF DEFECT AREA
LSEL,A,LOC,X,X7                      ! SELECT RIGHT EDGE OF DEFECT AREA
LSEL,A,LOC,Y,Y0                      ! SELECT FRONT EDGE OF DEFECT AREA
LSEL,A,LOC,Y,Y7                      ! SELECT BACK EDGE OF DEFECT AREA
LSEL,R,LOC,Z,0                       ! SELECT LINES AT MIDPLANE
LSEL,A,LINE,,L_NUM+1,L_NUM+4         ! ADD GLOBAL PLATE BOUNDARY LINES

AL,ALL                               ! CREATE GLOBAL PLATE FROM SELECTED LINES

! UNIQUE TO 4-POINT BEND CONFIGURATION !

K,K_NUM+5,A_SPAN,0,                  ! LEFT LOAD LINE FRONT KP
K,K_NUM+6,A_SPAN,W_PNL,              ! LEFT LOAD LINE BACK KP
K,K_NUM+7,L_PNL-A_SPAN,0,            ! RIGHT LOAD LINE FRONT KP
K,K_NUM+8,L_PNL-A_SPAN,W_PNL,        ! RIGHT LOAD LINE BACK KP
L,K_NUM+5,K_NUM+6                    ! LEFT LOAD LINE
L,K_NUM+7,K_NUM+8                    ! RIGHT LOAD LINE

LSEL,S,LINE,,L_NUM+5,L_NUM+6         ! SELECT LOAD LINES
ASBL,A_NUM+1,ALL,,DELETE,KEEP        ! SPLIT PLATE INTO 3 AREAS

!=============================================================================================!
!                                  APPLY MESH                                                 !
!=============================================================================================!

MSHAPE                          ! 2D ELEM ARE QUADS - 3D ELEM ARE HEX
MSHKEY,2                        ! USE MAPPED MESHING IF POSSIBLE

! DEFINE ELEMENT SIZE (MESH SEEDS) AROUND DEFECT REGION !

LSEL,S,TAN1,Z                   ! SELECT ALL HORIZ LINES
LSEL,R,LOC,X,X0,X7              ! DROP LINES OUTSIDE DEFECT REGION
LSEL,R,LOC,Y,Y0,Y7
LSEL,U,LOC,X,X0,X1              ! KEEP LINES FROM X1-X3 & X4-X6
LSEL,U,LOC,X,X3,X4
LSEL,U,LOC,X,X6,X7
LSEL,U,LOC,X,X2                 ! DROP LINES IN Y-DIR
LSEL,U,LOC,X,X5
LESIZE,ALL,DEL_F                ! SET LINE DIVS BASED ON DEL_F

LSEL,S,TAN1,Z                   ! SELECT ALL HORIZ LINES
LSEL,R,LOC,X,X0,X7              ! DROP LINES OUTSIDE DEFECT REGION
LSEL,R,LOC,Y,Y0,Y7
LSEL,U,LOC,Y,Y0,Y1              ! KEEP LINES FROM Y1-Y3 & Y4-Y6
LSEL,U,LOC,Y,Y3,Y4
LSEL,U,LOC,Y,Y6,Y7
LSEL,U,LOC,Y,Y2                 ! DROP LINES IN X-DIR
LSEL,U,LOC,Y,Y5
LESIZE,ALL,DEL_F                ! SET LINE DIVS BASED ON DEL_F

LSEL,S,LOC,X,(X0+X1)/2          ! SEELCT HORIZ LINES FROM X0-X1
LSEL,A,LOC,X,(X3+X4)/2          ! SELECT HORIZ LINES FROM X3-X4
LSEL,A,LOC,X,(X6+X7)/2          ! SEELCT HORIZ LINES FROM X6-X7
LSEL,A,LOC,Y,(Y0+Y1)/2          ! SEELCT HORIZ LINES FROM Y0-Y1
LSEL,A,LOC,Y,(Y3+Y4)/2          ! SELECT HORIZ LINES FROM Y3-Y4
LSEL,A,LOC,Y,(Y6+Y7)/2          ! SEELCT HORIZ LINES FROM Y6-Y7
LSEL,R,LOC,X,X0,X7              ! DROP LINES OUTSIDE DEFECT REGION
LSEL,R,LOC,Y,Y0,Y7
LESIZE,ALL,DEL_C                ! SET LINE DIVS BASED ON DEL_C

LSEL,S,TAN1,Z                   ! SELECT ALL HORIZONTAL LINES
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LSEL,INVE                      ! INVERT SELECTION - SELECT ALL VERTICAL LINES
LESIZE,ALL,DEL_Z               ! ADJUST LINE DIVS BASED ON Z-DIR MESH

! MESH DEFECT REGION !

TMP_Z1=SHIFT                         ! Z COORD OF BOT OF CURRENT PLY
*DO,OO,1,N_PLY
   TMP_Z2=TMP_Z1+T_PLY(OO)           ! Z COORD OF TOP OF CURRENT PLY
   VSEL,S,LOC,Z,TMP_Z1,TMP_Z2        ! SELECT VOLUMES IN CURRENT PLY
   VATT,MATL_N(OO),,2                ! ASSIGN MATL,,ELEM TYPE
   VMESH,ALL                         ! MESH SELECTED VOLUMES
   TMP_Z1=TMP_Z1+T_PLY(OO)           ! INDEX TO BOT OF NEXT PLY
*ENDDO

! MESH GLOBAL PLATE REGION !

ASEL,S,AREA,,A_NUM+2,A_NUM+4         ! SELECT GLOBAL PLATE AREAS (4PB LOAD CASE)
AATT,,,1,,1                          ! ASSIGN ,,,ELEM TYPE,,SECTION ID
ESIZE,DEL_S                          ! SET GLOBAL ELEMENT SIZE
AMESH,ALL                            ! MESH SELECTED AREA

!=============================================================================!
!                    APPLY CONSTRAINT EQUATIONS (MPC'S)                       !
!=============================================================================!

!NSEL,S,LOC,Z,SHIFT,SHIFT+T_DEL      ! SELECT NODES BELOW DELAM
!ESLN,S,1                            ! SELECT ELEMS BELOW DELAM
!/COLOR,ELEM,YELL                    ! DISPLAY AS YELLOW FOR VISUAL CONFIRMATION
!ESEL,ALL
/VIEW,1,1,-1,1                       ! ALTERNATE ISOMETRIC VIEW (Z-DIR UP)
/ANG,1,-60
/REP,FAST


! CREATE ARRAY OF NODES & COORDS !

NSEL,ALL                             ! SELECT ALL NODES
*GET,N_NUM,NODE,,COUNT               ! TOTAL NUMBER OF NODES
*DIM,N_ALL,ARRAY,N_NUM,4             ! DIMENSION ARRAY FOR NODES W/COORDS
*VGET,N_ALL(1,1),NODE,,NLIST         ! STORE ALL NODE NUMS
*VGET,N_ALL(1,2),NODE,,LOC,X         ! STORE ALL X COORDS
*VGET,N_ALL(1,3),NODE,,LOC,Y         ! STORE ALL Y COORDS
*VGET,N_ALL(1,4),NODE,,LOC,Z         ! STORE ALL Z COORDS

! COUNT NUMBER OF NODES THRU THICKNESS !

NSEL,S,LOC,X,X0                      ! SELECT NODES ON LEFT PLANE OF DEFECT REGION
NSEL,R,LOC,Y,Y0                      ! KEEP ONLY ONE VERTICAL LINE OF NODES
*GET,N_TMP,NODE,,COUNT               ! TOTAL NUMBER OF SELECTED NODES

! CREATE "MASKING" MATRIX FOR LEFT FACE !

*DIM,MASK1,ARRAY,N_NUM               ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,X,X0                      ! SELECT NODES ON LEFT PLANE OF DEFECT REGION
NSEL,R,LOC,Y,Y0,Y7                   ! KEEP ONLY NODES ON SOLID ELEMENTS
*VGET,MASK1(1,1),NODE,,NSEL          ! STORE NODE SELECTION STATUS (MASKING)
NPLOT

! REDUCE FULL MATRIX TO LEFT FACE ONLY !

*GET,N_SEL,NODE,,COUNT               ! TOTAL NUMBER OF SELECTED NODES
*DIM,N_TMP1,ARRAY,N_SEL,4            ! DIMENSION ARRAY FOR LEFT FACE NODES
*VMASK,MASK1                         ! VECTOR OF NODE SELECTION STATUS
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*VFUN,N_TMP1(1,1),COMP,N_ALL(1,1)   ! COMPRESS NODE NUMBERS
*VMASK,MASK1                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP1(1,2),COMP,N_ALL(1,2)   ! COMPRESS X COORDS
*VMASK,MASK1                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP1(1,3),COMP,N_ALL(1,3)   ! COMPRESS Y COORDS
*VMASK,MASK1                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP1(1,4),COMP,N_ALL(1,4)   ! COMPRESS Z COORDS

! CONSTRUCT CE'S ON LEFT FACE !

SORT2D,'N_TMP1',3,4,,0.001          ! SORT BY Y THEN Z  (0.001 SPATIAL TOLER) -MACRO
*DO,PP,1,N_SEL,N_TMP
   NSEL,S,NODE,,N_TMP1(PP)          ! SELECT ONE COLUMN OF NODES
   *DO,QQ,PP+1,PP+N_TMP-1
      NSEL,A,NODE,,N_TMP1(QQ)
   *ENDDO
   CERIG,NODE(X0,NY(N_TMP1(PP)),0),ALL,UXYZ     ! BUILD CONSTRAINT EQUATIONS
*ENDDO                                          !(MASTER NODE IS AT MIDPLANE)

! CREATE "MASKING" MATRIX FOR RIGHT FACE !

*DIM,MASK2,ARRAY,N_NUM              ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,X,X7                     ! SELECT NODES ON RIGHT PLANE OF DEFECT REGION
NSEL,R,LOC,Y,Y0,Y7                  ! ONLY NODES ON SOLID ELEMENTS
*VGET,MASK2(1,1),NODE,,NSEL         ! STORE NODE SELECTION STATUS (MASKING)
NPLOT

! REDUCE FULL MATRIX TO RIGHT FACE ONLY !

*GET,N_SEL,NODE,,COUNT              ! TOTAL NUMBER OF SELECTED NODES
*DIM,N_TMP2,ARRAY,N_SEL,4           ! DIMENSION ARRAY FOR RIGHT FACE NODES
*VMASK,MASK2                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP2(1,1),COMP,N_ALL(1,1)   ! COMPRESS NODE NUMBERS
*VMASK,MASK2                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP2(1,2),COMP,N_ALL(1,2)   ! COMPRESS X COORDS
*VMASK,MASK2                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP2(1,3),COMP,N_ALL(1,3)   ! COMPRESS Y COORDS
*VMASK,MASK2                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP2(1,4),COMP,N_ALL(1,4)   ! COMPRESS Z COORDS

! CONSTRUCT CE'S ON RIGHT FACE !

SORT2D,'N_TMP2',3,4,,0.001          ! SORT BY Y THEN Z  (0.001 SPATIAL TOLER) -MACRO
*DO,PP,1,N_SEL,N_TMP
   NSEL,S,NODE,,N_TMP2(PP)          ! SELECT ONE COLUMN OF NODES
   *DO,QQ,PP+1,PP+N_TMP-1
      NSEL,A,NODE,,N_TMP2(QQ)
   *ENDDO
   CERIG,NODE(X7,NY(N_TMP2(PP)),0),ALL,UXYZ     ! BUILD CONSTRAINT EQUATIONS
*ENDDO                                          !(MASTER NODE IS AT MIDPLANE)

! CREATE "MASKING" MATRIX FOR FRONT FACE !

*DIM,MASK3,ARRAY,N_NUM              ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,Y,Y0                     ! SELECT NODES ON FRONT PLANE OF DEFECT REGION
NSEL,R,LOC,X,X0+DEL_F/2,X7-DEL_F/2  ! ONLY NODES ON SOLID ELEMENTS (EXCL CORNERS)
*VGET,MASK3(1,1),NODE,,NSEL         ! STORE NODE SELECTION STATUS (MASKING)
NPLOT

! REDUCE FULL MATRIX TO FRONT FACE ONLY !

*GET,N_SEL,NODE,,COUNT              ! TOTAL NUMBER OF SELECTED NODES
*DIM,N_TMP3,ARRAY,N_SEL,4           ! DIMENSION ARRAY FOR FRONT FACE NODES
```

```
*VMASK,MASK3                          ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP3(1,1),COMP,N_ALL(1,1)    ! COMPRESS NODE NUMBERS
*VMASK,MASK3                          ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP3(1,2),COMP,N_ALL(1,2)    ! COMPRESS X COORDS
*VMASK,MASK3                          ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP3(1,3),COMP,N_ALL(1,3)    ! COMPRESS Y COORDS
*VMASK,MASK3                          ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP3(1,4),COMP,N_ALL(1,4)    ! COMPRESS Z COORDS

! CONSTRUCT CE'S ON FRONT FACE !

SORT2D,'N_TMP3',2,4,,0.001           ! SORT BY X THEN Z  (0.001 SPATIAL TOLER) -MACRO
*DO,PP,1,N_SEL,N_TMP
   NSEL,S,NODE,,N_TMP3(PP)           ! SELECT ONE COLUMN OF NODES
   *DO,QQ,PP+1,PP+N_TMP-1
      NSEL,A,NODE,,N_TMP3(QQ)
   *ENDDO
   CERIG,NODE(NX(N_TMP3(PP)),Y0,0),ALL,UXYZ     ! BUILD CONSTRAINT EQUATIONS
*ENDDO                                          !(MASTER NODE IS AT MIDPLANE)

! CREATE "MASKING" MATRIX FOR BACK FACE !

*DIM,MASK4,ARRAY,N_NUM               ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,Y,Y7                      ! ONLY NODES ON BACK PLANE OF DEFECT REGION
NSEL,R,LOC,X,X0+DEL_F/2,X7-DEL_F/2   ! ONLY NODES ON SOLID ELEMENTS (EXCL CORNERS)
*VGET,MASK4(1,1),NODE,,NSEL          ! STORE NODE SELECTION STATUS (MASKING)
NPLOT

! REDUCE FULL MATRIX TO BACK FACE ONLY !

*GET,N_SEL,NODE,,COUNT               ! TOTAL NUMBER OF SELECTED NODES
*DIM,N_TMP4,ARRAY,N_SEL,4           ! DIMENSION ARRAY FOR BACK FACE NODES
*VMASK,MASK4                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP4(1,1),COMP,N_ALL(1,1)    ! COMPRESS NODE NUMBERS
*VMASK,MASK4                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP4(1,2),COMP,N_ALL(1,2)    ! COMPRESS X COORDS
*VMASK,MASK4                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP4(1,3),COMP,N_ALL(1,3)    ! COMPRESS Y COORDS
*VMASK,MASK4                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP4(1,4),COMP,N_ALL(1,4)    ! COMPRESS Z COORDS

! CONSTRUCT CE'S ON BACK FACE !

SORT2D,'N_TMP4',2,4,,0.001           ! SORT BY X THEN Z  (0.001 SPATIAL TOLER) -MACRO
*DO,PP,1,N_SEL,N_TMP
   NSEL,S,NODE,,N_TMP4(PP)           ! SELECT ONE COLUMN OF NODES
   *DO,QQ,PP+1,PP+N_TMP-1
      NSEL,A,NODE,,N_TMP4(QQ)
   *ENDDO
   CERIG,NODE(NX(N_TMP3(PP)),Y7,0),ALL,UXYZ     ! BUILD CONSTRAINT EQUATIONS
*ENDDO                                          !(MASTER NODE IS AT MIDPLANE)

ALLSEL,ALL,ELEM
!/ESHAPE,1                           ! SHOW 2D ELEMS WITH THICKNESS
EPLOT

!=============================================================================================!
!                          APPLY CONTACT ELEMENTS                                             !
!=============================================================================================!

NSEL,S,LOC,Z,Z1                      ! SELECT COINC NODES AT DELAM INTERFACE !
NSEL,R,LOC,X,X2+DEL_F/2,X5-DEL_F/2
NSEL,R,LOC,Y,Y2+DEL_F/2,Y5-DEL_F/2
```

```
TYPE,3                              ! CONTA178 IS ACTIVE ELEM TYPE
REAL,1                              ! CONTA178 REAL CONSTANTS ARE ACTIVE
EINTF,0.0001,,LOW                   ! BUILD CONTACT ELEMENTS

!=============================================================================================!
!                         APPLY BOUNDARY CONDITIONS                                           !
!=============================================================================================!

! UNIQUE TO 4-POINT BEND TEST CONFIGURATION !

NSEL,S,LOC,X,0                  ! SELECT NODES AT LEFT SUPPORT
NSEL,A,LOC,X,L_PNL              ! ALSO SELECT NODES AT RIGHT SUPPORT
D,ALL,UZ,0                      ! VERTICAL DISP = 0
NSEL,R,LOC,Y,0                  ! SELECT LWR LEFT & RIGHT CORNER NODES
D,ALL,UY,0                      ! TRANSVERSE DISP = 0

NSEL,S,LOC,X,A_SPAN             ! SELECT NODES AT LEFT LOAD LINE
*GET,LL_NODE,NODE,,COUNT        ! GET NUMBER OF NODES IN SET
D,ALL,UX,0                      ! LONGITUDINAL DISP = 0 (X-DIR BC)
NSEL,A,LOC,X,L_PNL-A_SPAN       ! ALSO SELECT NODES AT RIGHT LOAD LINE
F,ALL,FZ,FORCE/LL_NODE          ! APPLY "LINE" LOADS TO ALL NODES

! %%% THESE LOADS ARE ONLY USED FOR MODEL VERIFICATION %%% !

!NSEL,S,LOC,Z,SHIFT                                 ! THESE COMMAND LINES ARE     %%%
!NSEL,R,LOC,X,XD_DEL-1.2*DEL_C,XD_DEL+1.2*DEL_C
!NSEL,R,LOC,Y,YD_DEL-1.2*DEL_C,YD_DEL+1.2*DEL_C ! ONLY USED TO CHECK THE      %%%
!*GET,N_SEL,NODE,,COUNT
!F,ALL,FZ,-1/N_SEL                                 ! CONTACT ELEMENTS AND        %%%
!NSEL,S,LOC,Z,-SHIFT
!NSEL,R,LOC,X,XD_DEL-1.2*DEL_C,XD_DEL+1.2*DEL_C ! EFFECT OF OPPOSING          %%%
!NSEL,R,LOC,Y,YD_DEL-1.2*DEL_C,YD_DEL+1.2*DEL_C
!F,ALL,FZ,1/N_SEL                                  ! LOADS ON GI SERR            %%%


FINISH

!=============================================================================================!
!                                  SOLVE MODEL                                                !
!=============================================================================================!

ALLSEL                          ! SELECT EVERYTHING
/SOLU                           ! ENTER SOLVER
NLGEOM,OFF                      ! NONLINEAR GEOMETRY OFF
!PRED,OFF                       ! NO PREDICTION OCCURS
ANTYPE,0                        ! NEW STATIC ANALYSIS
TIME,1                          ! SET TIME AT END OF LOAD STEP
SOLVE                           ! SOLVE MODEL

FINISH

!=============================================================================================!
!                        GET NODAL FORCES (ZI,XI)                                             !
!=============================================================================================!

/PREP7                              ! ENTER PREPROCESSOR

! CREATE "MASKING" MATRIX -ALONG- LEFT EDGE !

*DIM,MASK5,ARRAY,N_NUM              ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,X,X2                     ! SELECT NODES IN PLANE OF LEFT CRACK FRONT
NSEL,R,LOC,Z,Z1                     ! SELECT NODES AT DEPTH OF DELAM
NSEL,R,LOC,Y,Y2,Y5                  ! SELECT NODES ALONG LEFT EDGE OF DELAM
```

```
*VGET,MASK5(1,1),NODE,,NSEL         ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -ALONG- LEFT EDGE !

*GET,LCRK_N,NODE,,COUNT             ! GET NUMBER OF NODES IN SET
*DIM,N_TMP5,ARRAY,LCRK_N,4          ! DIMENSION ARRAY FOR LEFT EDGE NODES
*VMASK,MASK5                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP5(1,1),COMP,N_ALL(1,1)   ! COMPRESS NODE NUMBERS
*VMASK,MASK5                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP5(1,2),COMP,N_ALL(1,2)   ! COMPRESS X COORDS
*VMASK,MASK5                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP5(1,3),COMP,N_ALL(1,3)   ! COMPRESS Y COORDS
*VMASK,MASK5                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP5(1,4),COMP,N_ALL(1,4)   ! COMPRESS Z COORDS
SORT2D,'N_TMP5',3,,,0.001           ! SORT BY Y  (0.001 SPATIAL TOLER) -MACRO

! CREATE "MASKING" MATRIX -ABOVE- LEFT EDGE !

*DIM,MASK6,ARRAY,N_NUM              ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,X,X2                     ! SELECT NODES IN PLANE OF LEFT CRACK FRONT
NSEL,R,LOC,Z,Z1+T_PLY(D_PLY+1)      ! SELECT NODES ABOVE DEPTH OF DELAM
NSEL,R,LOC,Y,Y2,Y5                  ! SELECT NODES ALONG LEFT EDGE OF DELAM
*VGET,MASK6(1,1),NODE,,NSEL         ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -ABOVE- LEFT EDGE !

*DIM,N_TMP6,ARRAY,LCRK_N,4          ! DIMENSION ARRAY FOR LEFT EDGE NODES
*VMASK,MASK6                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP6(1,1),COMP,N_ALL(1,1)   ! COMPRESS NODE NUMBERS
*VMASK,MASK6                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP6(1,2),COMP,N_ALL(1,2)   ! COMPRESS X COORDS
*VMASK,MASK6                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP6(1,3),COMP,N_ALL(1,3)   ! COMPRESS Y COORDS
*VMASK,MASK6                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP6(1,4),COMP,N_ALL(1,4)   ! COMPRESS Z COORDS
SORT2D,'N_TMP6',3,,,0.001           ! SORT BY Y  (0.001 SPATIAL TOLER) -MACRO

! CREATE "MASKING" MATRIX -ALONG- RIGHT EDGE !

*DIM,MASK7,ARRAY,N_NUM              ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,X,X5                     ! SELECT NODES IN PLANE OF RIGHT CRACK FRONT
NSEL,R,LOC,Z,Z1                     ! SELECT NODES AT DEPTH OF DELAM
NSEL,R,LOC,Y,Y2,Y5                  ! SELECT NODES ALONG RIGHT EDGE OF DELAM
*VGET,MASK7(1,1),NODE,,NSEL         ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -ALONG- RIGHT EDGE !

*GET,RCRK_N,NODE,,COUNT             ! GET NUMBER OF NODES IN SET
*DIM,N_TMP7,ARRAY,RCRK_N,4          ! DIMENSION ARRAY FOR RIGHT EDGE NODES
*VMASK,MASK7                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP7(1,1),COMP,N_ALL(1,1)   ! COMPRESS NODE NUMBERS
*VMASK,MASK7                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP7(1,2),COMP,N_ALL(1,2)   ! COMPRESS X COORDS
*VMASK,MASK7                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP7(1,3),COMP,N_ALL(1,3)   ! COMPRESS Y COORDS
*VMASK,MASK7                        ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP7(1,4),COMP,N_ALL(1,4)   ! COMPRESS Z COORDS
SORT2D,'N_TMP7',3,,,0.001           ! SORT BY Y  (0.001 SPATIAL TOLER) -MACRO

! CREATE "MASKING" MATRIX -ABOVE- RIGHT EDGE !

*DIM,MASK8,ARRAY,N_NUM              ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,X,X5                     ! SELECT NODES IN PLANE OF RIGHT CRACK FRONT
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```
NSEL,R,LOC,Z,Z1+T_PLY(D_PLY+1)      ! SELECT NODES ABOVE DEPTH OF DELAM
NSEL,R,LOC,Y,Y2,Y5                  ! SELECT NODES ALONG RIGHT EDGE OF DELAM
*VGET,MASK8(1,1),NODE,,NSEL         ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -ABOVE- RIGHT EDGE !

*DIM,N_TMP8,ARRAY,RCRK_N,4          ! DIMENSION ARRAY FOR RIGHT EDGE NODES
*VMASK,MASK8                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP8(1,1),COMP,N_ALL(1,1)  ! COMPRESS NODE NUMBERS
*VMASK,MASK8                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP8(1,2),COMP,N_ALL(1,2)  ! COMPRESS X COORDS
*VMASK,MASK8                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP8(1,3),COMP,N_ALL(1,3)  ! COMPRESS Y COORDS
*VMASK,MASK8                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP8(1,4),COMP,N_ALL(1,4)  ! COMPRESS Z COORDS
SORT2D,'N_TMP8',3,,,0.001           ! SORT BY Y  (0.001 SPATIAL TOLER) -MACRO

! CREATE "MASKING" MATRIX -ALONG- FRONT EDGE !

*DIM,MASK9,ARRAY,N_NUM              ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,Y,Y2                     ! SELECT NODES IN PLANE OF FRONT CRACK FRONT
NSEL,R,LOC,Z,Z1                     ! SELECT NODES AT DEPTH OF DELAM
NSEL,R,LOC,X,X2,X5                  ! SELECT NODES ALONG FRONT EDGE OF DELAM
*VGET,MASK9(1,1),NODE,,NSEL         ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -ALONG- FRONT EDGE !

*GET,FCRK_N,NODE,,COUNT             ! GET NUMBER OF NODES IN SET
*DIM,N_TMP9,ARRAY,FCRK_N,4          ! DIMENSION ARRAY FOR FRONT EDGE NODES
*VMASK,MASK9                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP9(1,1),COMP,N_ALL(1,1)  ! COMPRESS NODE NUMBERS
*VMASK,MASK9                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP9(1,2),COMP,N_ALL(1,2)  ! COMPRESS X COORDS
*VMASK,MASK9                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP9(1,3),COMP,N_ALL(1,3)  ! COMPRESS Y COORDS
*VMASK,MASK9                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP9(1,4),COMP,N_ALL(1,4)  ! COMPRESS Z COORDS
SORT2D,'N_TMP9',2,,,0.001           ! SORT BY X  (0.001 SPATIAL TOLER) -MACRO

! CREATE "MASKING" MATRIX -ABOVE- FRONT EDGE !

*DIM,MASK10,ARRAY,N_NUM             ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,Y,Y2                     ! SELECT NODES IN PLANE OF FRONT CRACK FRONT
NSEL,R,LOC,Z,Z1+T_PLY(D_PLY+1)      ! SELECT NODES ABOVE DEPTH OF DELAM
NSEL,R,LOC,X,X2,X5                  ! SELECT NODES ALONG FRONT EDGE OF DELAM
*VGET,MASK10(1,1),NODE,,NSEL        ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -ABOVE- FRONT EDGE !

*DIM,N_TMP10,ARRAY,FCRK_N,4         ! DIMENSION ARRAY FOR FRONT EDGE NODES
*VMASK,MASK10                      ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP10(1,1),COMP,N_ALL(1,1) ! COMPRESS NODE NUMBERS
*VMASK,MASK10                      ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP10(1,2),COMP,N_ALL(1,2) ! COMPRESS X COORDS
*VMASK,MASK10                      ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP10(1,3),COMP,N_ALL(1,3) ! COMPRESS Y COORDS
*VMASK,MASK10                      ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP10(1,4),COMP,N_ALL(1,4) ! COMPRESS Z COORDS
SORT2D,'N_TMP10',2,,,0.001          ! SORT BY X  (0.001 SPATIAL TOLER) -MACRO

! CREATE "MASKING" MATRIX -ALONG- BACK EDGE !

*DIM,MASK11,ARRAY,N_NUM             ! DIMENSION ARRAY FOR SELECTION STATUS
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```
NSEL,S,LOC,Y,Y5                     ! SELECT NODES IN PLANE OF BACK CRACK FRONT
NSEL,R,LOC,Z,Z1                     ! SELECT NODES AT DEPTH OF DELAM
NSEL,R,LOC,X,X2,X5                  ! SELECT NODES ALONG BACK EDGE OF DELAM
*VGET,MASK11(1,1),NODE,,NSEL        ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -ALONG- BACK EDGE !

*GET,BCRK_N,NODE,,COUNT             ! GET NUMBER OF NODES IN SET
*DIM,N_TMP11,ARRAY,BCRK_N,4         ! DIMENSION ARRAY FOR BACK EDGE NODES
*VMASK,MASK11                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP11(1,1),COMP,N_ALL(1,1)  ! COMPRESS NODE NUMBERS
*VMASK,MASK11                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP11(1,2),COMP,N_ALL(1,2)  ! COMPRESS X COORDS
*VMASK,MASK11                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP11(1,3),COMP,N_ALL(1,3)  ! COMPRESS Y COORDS
*VMASK,MASK11                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP11(1,4),COMP,N_ALL(1,4)  ! COMPRESS Z COORDS
SORT2D,'N_TMP11',2,,,0.001          ! SORT BY X  (0.001 SPATIAL TOLER) -MACRO

! CREATE "MASKING" MATRIX -ABOVE- BACK EDGE !

*DIM,MASK12,ARRAY,N_NUM             ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,Y,Y5                     ! SELECT NODES IN PLANE OF BACK CRACK FRONT
NSEL,R,LOC,Z,Z1+T_PLY(D_PLY+1)      ! SELECT NODES ABOVE DEPTH OF DELAM
NSEL,R,LOC,X,X2,X5                  ! SELECT NODES ALONG BACK EDGE OF DELAM
*VGET,MASK12(1,1),NODE,,NSEL        ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -ABOVE- BACK EDGE !

*DIM,N_TMP12,ARRAY,BCRK_N,4         ! DIMENSION ARRAY FOR BACK EDGE NODES
*VMASK,MASK12                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP12(1,1),COMP,N_ALL(1,1)  ! COMPRESS NODE NUMBERS
*VMASK,MASK12                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP12(1,2),COMP,N_ALL(1,2)  ! COMPRESS X COORDS
*VMASK,MASK12                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP12(1,3),COMP,N_ALL(1,3)  ! COMPRESS Y COORDS
*VMASK,MASK12                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP12(1,4),COMP,N_ALL(1,4)  ! COMPRESS Z COORDS
SORT2D,'N_TMP12',2,,,0.001          ! SORT BY X  (0.001 SPATIAL TOLER) -MACRO

FINISH

! DISPLAY DISPLACED SHAPE !

CSYS,0                              ! ACTIVE CS SET TO CARTESIAN
/POST1                              ! ENTER POSTPROCESSOR
PLDISP,2                            ! PLOT DISP SHAPE WITH ORIG WIRE FRAME

! SELECT NODES AT CRACK TIP - SUM UPPER CONNECTING ELEMENTS

*DIM,L_ZI,ARRAY,LCRK_N-2            ! DIM ARRAY FOR LEFT EDGE FORCES (AVOID CRNRS)
*DIM,L_XI,ARRAY,LCRK_N-2
*DO,QQ,1,LCRK_N-2
   NSEL,S,NODE,,N_TMP6(QQ+1)        ! SELECT NODE ABOVE LEFT EDGE
   ESLN,S                           ! SELECT ELEMENTS CONNECTED TO NODE
   NSEL,S,NODE,,N_TMP5(QQ+1)        ! SELECT NODE ALONG LEFT EDGE
   FSUM
   *GET,L_ZI(QQ),FSUM,0,ITEM,FZ     ! SETS Zi = FORCE AT CRACK TIP IN Z DIRECTION
   *GET,L_XI(QQ),FSUM,0,ITEM,FX     ! SETS Xi = FORCE AT CRACK TIP IN X DIRECTION
*ENDDO

*DIM,R_ZI,ARRAY,RCRK_N-2            ! DIM ARRAY FOR RIGHT EDGE FORCES (AVOID CRNRS)
*DIM,R_XI,ARRAY,RCRK_N-2
```

```
*DO,RR,1,RCRK_N-2
   NSEL,S,NODE,,N_TMP8(RR+1)        ! SELECT NODE ABOVE RIGHT EDGE
   ESLN,S                           ! SELECT ELEMENTS CONNECTED TO NODE
   NSEL,S,NODE,,N_TMP7(RR+1)        ! SELECT NODE ALONG RIGHT EDGE
   FSUM
   *GET,R_ZI(RR),FSUM,0,ITEM,FZ     ! SETS Zi = FORCE AT CRACK TIP IN Z DIRECTION
   *GET,R_XI(RR),FSUM,0,ITEM,FX     ! SETS Xi = FORCE AT CRACK TIP IN X DIRECTION
*ENDDO

*DIM,F_ZI,ARRAY,FCRK_N-2            ! DIM ARRAY FOR FRONT EDGE FORCES (AVOID CRNRS)
*DIM,F_XI,ARRAY,FCRK_N-2
*DO,SS,1,FCRK_N-2
   NSEL,S,NODE,,N_TMP10(SS+1)       ! SELECT NODE ABOVE FRONT EDGE
   ESLN,S                           ! SELECT ELEMENTS CONNECTED TO NODE
   NSEL,S,NODE,,N_TMP9(SS+1)        ! SELECT NODE ALONG FRONT EDGE
   FSUM
   *GET,F_ZI(SS),FSUM,0,ITEM,FZ     ! SETS Zi = FORCE AT CRACK TIP IN Z DIRECTION
   *GET,F_XI(SS),FSUM,0,ITEM,FX     ! SETS Xi = FORCE AT CRACK TIP IN X DIRECTION
*ENDDO

*DIM,B_ZI,ARRAY,BCRK_N-2            ! DIM ARRAY FOR BACK EDGE FORCES (AVOID CRNRS)
*DIM,B_XI,ARRAY,BCRK_N-2
*DO,TT,1,BCRK_N-2
   NSEL,S,NODE,,N_TMP12(TT+1)       ! SELECT NODE ABOVE BACK EDGE
   ESLN,S                           ! SELECT ELEMENTS CONNECTED TO NODE
   NSEL,S,NODE,,N_TMP11(TT+1)       ! SELECT NODE ALONG BACK EDGE
   FSUM
   *GET,B_ZI(TT),FSUM,0,ITEM,FZ     ! SETS Zi = FORCE AT CRACK TIP IN Z DIRECTION
   *GET,B_XI(TT),FSUM,0,ITEM,FX     ! SETS Xi = FORCE AT CRACK TIP IN X DIRECTION
*ENDDO

FINISH

!=============================================================================================!
!                  GET NODAL DEFORMATIONS (WL,WL*,UL,UL*)                      !
!=============================================================================================!

/PREP7                              ! ENTER PREPROCESSOR

! CREATE "MASKING" MATRIX -INSIDE- LEFT EDGE !

*DIM,MASK13,ARRAY,N_NUM                   ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,X,X2+0.5*DEL_F,X2+1.5*DEL_F    ! SELECT NODES INTERIOR TO LEFT CRACK FRONT
NSEL,R,LOC,Z,Z1                           ! SELECT NODES AT DEPTH OF DELAM
NSEL,R,LOC,Y,Y2,Y5                        ! SELECT NODES WITHIN CRACK REGION
*VGET,MASK13(1,1),NODE,,NSEL             ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -INSIDE- LEFT EDGE !

*GET,LCRK_N,NODE,,COUNT             ! GET NUMBER OF NODES IN SET
*DIM,N_TMP13,ARRAY,LCRK_N,4         ! DIMENSION ARRAY FOR LEFT INTERIOR NODES
*VMASK,MASK13                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP13(1,1),COMP,N_ALL(1,1)  ! COMPRESS NODE NUMBERS
*VMASK,MASK13                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP13(1,2),COMP,N_ALL(1,2)  ! COMPRESS X COORDS
*VMASK,MASK13                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP13(1,3),COMP,N_ALL(1,3)  ! COMPRESS Y COORDS
*VMASK,MASK13                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP13(1,4),COMP,N_ALL(1,4)  ! COMPRESS Z COORDS
SORT2D,'N_TMP13',3,,,0.001          ! SORT BY Y  (0.001 SPATIAL TOLER) -MACRO

! CREATE "MASKING" MATRIX -INSIDE- RIGHT EDGE !
```

```
*DIM,MASK14,ARRAY,N_NUM                    ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,X,X5-1.5*DEL_F,X5-0.5*DEL_F     ! SELECT NODES INTERIOR TO RIGHT CRACK FRONT
NSEL,R,LOC,Z,Z1                            ! SELECT NODES AT DEPTH OF DELAM
NSEL,R,LOC,Y,Y2,Y5                         ! SELECT NODES WITHIN CRACK REGION
*VGET,MASK14(1,1),NODE,,NSEL               ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -INSIDE- RIGHT EDGE !

*GET,RCRK_N,NODE,,COUNT                ! GET NUMBER OF NODES IN SET
*DIM,N_TMP14,ARRAY,RCRK_N,4           ! DIMENSION ARRAY FOR RIGHT INTERIOR NODES
*VMASK,MASK14                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP14(1,1),COMP,N_ALL(1,1)    ! COMPRESS NODE NUMBERS
*VMASK,MASK14                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP14(1,2),COMP,N_ALL(1,2)    ! COMPRESS X COORDS
*VMASK,MASK14                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP14(1,3),COMP,N_ALL(1,3)    ! COMPRESS Y COORDS
*VMASK,MASK14                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP14(1,4),COMP,N_ALL(1,4)    ! COMPRESS Z COORDS
SORT2D,'N_TMP14',3,,,0.001             ! SORT BY Y  (0.001 SPATIAL TOLER) -MACRO

! CREATE "MASKING" MATRIX -INSIDE- FRONT EDGE !

*DIM,MASK15,ARRAY,N_NUM                    ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,Y,Y2+0.5*DEL_F,Y2+1.5*DEL_F     ! SELECT NODES INTERIOR TO FRONT CRACK FRONT
NSEL,R,LOC,Z,Z1                            ! SELECT NODES AT DEPTH OF DELAM
NSEL,R,LOC,X,X2,X5                         ! SELECT NODES WITHIN CRACK REGION
*VGET,MASK15(1,1),NODE,,NSEL               ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -INSIDE- FRONT EDGE !

*GET,FCRK_N,NODE,,COUNT                ! GET NUMBER OF NODES IN SET
*DIM,N_TMP15,ARRAY,FCRK_N,4           ! DIMENSION ARRAY FOR FRONT INTERIOR NODES
*VMASK,MASK15                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP15(1,1),COMP,N_ALL(1,1)    ! COMPRESS NODE NUMBERS
*VMASK,MASK15                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP15(1,2),COMP,N_ALL(1,2)    ! COMPRESS X COORDS
*VMASK,MASK15                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP15(1,3),COMP,N_ALL(1,3)    ! COMPRESS Y COORDS
*VMASK,MASK15                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP15(1,4),COMP,N_ALL(1,4)    ! COMPRESS Z COORDS
SORT2D,'N_TMP15',2,,,0.001             ! SORT BY X  (0.001 SPATIAL TOLER) -MACRO

! CREATE "MASKING" MATRIX -INSIDE- BACK EDGE !

*DIM,MASK16,ARRAY,N_NUM                    ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,Y,Y5-1.5*DEL_F,Y5-0.5*DEL_F     ! SELECT NODES INTERIOR TO BACK CRACK FRONT
NSEL,R,LOC,Z,Z1                            ! SELECT NODES AT DEPTH OF DELAM
NSEL,R,LOC,X,X2,X5                         ! SELECT NODES WITHIN CRACK REGION
*VGET,MASK16(1,1),NODE,,NSEL               ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -INSIDE- BACK EDGE !

*GET,BCRK_N,NODE,,COUNT                ! GET NUMBER OF NODES IN SET
*DIM,N_TMP16,ARRAY,BCRK_N,4           ! DIMENSION ARRAY FOR BACK INTERIOR NODES
*VMASK,MASK16                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP16(1,1),COMP,N_ALL(1,1)    ! COMPRESS NODE NUMBERS
*VMASK,MASK16                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP16(1,2),COMP,N_ALL(1,2)    ! COMPRESS X COORDS
*VMASK,MASK16                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP16(1,3),COMP,N_ALL(1,3)    ! COMPRESS Y COORDS
*VMASK,MASK16                         ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP16(1,4),COMP,N_ALL(1,4)    ! COMPRESS Z COORDS
SORT2D,'N_TMP16',2,,,0.001             ! SORT BY X  (0.001 SPATIAL TOLER) -MACRO
```

```
FINISH

! SELECT INTERIOR NODE NEAR CRACK TIP

/POST1

*DIM,L_WL,ARRAY,(LCRK_N-2)/2        ! DIM ARRAYS FOR LEFT EDGE DISP (AVOID CRNRS)
*DIM,L_UL,ARRAY,(LCRK_N-2)/2
*DIM,L_WLS,ARRAY,(LCRK_N-2)/2
*DIM,L_ULS,ARRAY,(LCRK_N-2)/2
*DO,UU,2,LCRK_N-2,2
   NSEL,S,NODE,,N_TMP13(UU)         ! SELECT COINCIDENT NODES
   NSEL,A,NODE,,N_TMP13(UU+1)
   *GET,NODE_L,NODE,0,NUM,MAX       ! GET MAX NODE # (UPR NODE)
   *GET,NODE_LS,NODE,0,NUM,MIN      ! GET MIN NODE # (LWR NODE)
   L_WL(UU/2)=UZ(NODE_L)            ! VERTICAL DISP OF NODE L
   L_WLS(UU/2)=UZ(NODE_LS)          ! VERTICAL DISP OF NODE L*
   L_UL(UU/2)=UX(NODE_L)            ! HORIZONTAL DISP OF NODE L
   L_ULS(UU/2)=UX(NODE_LS)          ! HORIZONTAL DISP OF NODE L*
*ENDDO

*DIM,R_WL,ARRAY,(RCRK_N-2)/2        ! DIM ARRAYS FOR RIGHT EDGE DISP (AVOID CRNRS)
*DIM,R_UL,ARRAY,(RCRK_N-2)/2
*DIM,R_WLS,ARRAY,(RCRK_N-2)/2
*DIM,R_ULS,ARRAY,(RCRK_N-2)/2
*DO,VV,2,RCRK_N-2,2
   NSEL,S,NODE,,N_TMP14(VV)         ! SELECT COINCIDENT NODES
   NSEL,A,NODE,,N_TMP14(VV+1)
   *GET,NODE_L,NODE,0,NUM,MAX       ! GET MAX NODE # (UPR NODE)
   *GET,NODE_LS,NODE,0,NUM,MIN      ! GET MIN NODE # (LWR NODE)
   R_WL(VV/2)=UZ(NODE_L)            ! VERTICAL DISP OF NODE L
   R_WLS(VV/2)=UZ(NODE_LS)          ! VERTICAL DISP OF NODE L*
   R_UL(VV/2)=UX(NODE_L)            ! HORIZONTAL DISP OF NODE L
   R_ULS(VV/2)=UX(NODE_LS)          ! HORIZONTAL DISP OF NODE L*
*ENDDO

*DIM,F_WL,ARRAY,(FCRK_N-2)/2        ! DIM ARRAYS FOR FRONT EDGE DISP (AVOID CRNRS)
*DIM,F_UL,ARRAY,(FCRK_N-2)/2
*DIM,F_WLS,ARRAY,(FCRK_N-2)/2
*DIM,F_ULS,ARRAY,(FCRK_N-2)/2
*DO,WW,2,FCRK_N-2,2
   NSEL,S,NODE,,N_TMP15(WW)         ! SELECT COINCIDENT NODES
   NSEL,A,NODE,,N_TMP15(WW+1)
   *GET,NODE_L,NODE,0,NUM,MAX       ! GET MAX NODE # (UPR NODE)
   *GET,NODE_LS,NODE,0,NUM,MIN      ! GET MIN NODE # (LWR NODE)
   F_WL(WW/2)=UZ(NODE_L)            ! VERTICAL DISP OF NODE L
   F_WLS(WW/2)=UZ(NODE_LS)          ! VERTICAL DISP OF NODE L*
   F_UL(WW/2)=UX(NODE_L)            ! HORIZONTAL DISP OF NODE L
   F_ULS(WW/2)=UX(NODE_LS)          ! HORIZONTAL DISP OF NODE L*
*ENDDO

*DIM,B_WL,ARRAY,(BCRK_N-2)/2        ! DIM ARRAYS FOR BACK EDGE DISP (AVOID CRNRS)
*DIM,B_UL,ARRAY,(BCRK_N-2)/2
*DIM,B_WLS,ARRAY,(BCRK_N-2)/2
*DIM,B_ULS,ARRAY,(BCRK_N-2)/2
*DO,XX,2,BCRK_N-2,2
   NSEL,S,NODE,,N_TMP16(XX)         ! SELECT COINCIDENT NODES
   NSEL,A,NODE,,N_TMP16(XX+1)
   *GET,NODE_L,NODE,0,NUM,MAX       ! GET MAX NODE # (UPR NODE)
   *GET,NODE_LS,NODE,0,NUM,MIN      ! GET MIN NODE # (LWR NODE)
   B_WL(XX/2)=UZ(NODE_L)            ! VERTICAL DISP OF NODE L
   B_WLS(XX/2)=UZ(NODE_LS)          ! VERTICAL DISP OF NODE L*
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   B_UL(XX/2)=UX(NODE_L)            ! HORIZONTAL DISP OF NODE L
   B_ULS(XX/2)=UX(NODE_LS)          ! HORIZONTAL DISP OF NODE L*
*ENDDO

FINISH

!=============================================================================================!
!                  DETERMINE STRAIN ENERGY RELEASE RATE (SERR)                 !
!=============================================================================================!

/PREP7

! CREATE "MASKING" MATRIX -OUTSIDE- LEFT EDGE !

*DIM,MASK17,ARRAY,N_NUM                   ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,X,X2-1.5*DEL_F,X2-0.5*DEL_F    ! SELECT NODES EXTERIOR TO LEFT CRACK FRONT
NSEL,R,LOC,Z,Z1                           ! SELECT NODES AT DEPTH OF DELAM
NSEL,R,LOC,Y,Y2,Y5                        ! SELECT NODES EXTERIOR TO LEFT EDGE OF DELAM
*VGET,MASK17(1,1),NODE,,NSEL             ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -OUTSIDE- LEFT EDGE !

*GET,LCRK_N,NODE,,COUNT                   ! GET NUMBER OF NODES IN SET
*DIM,N_TMP17,ARRAY,LCRK_N,4              ! DIMENSION ARRAY FOR LEFT EXTERIOR NODES
*VMASK,MASK17                            ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP17(1,1),COMP,N_ALL(1,1)       ! COMPRESS NODE NUMBERS
*VMASK,MASK17                            ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP17(1,2),COMP,N_ALL(1,2)       ! COMPRESS X COORDS
*VMASK,MASK17                            ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP17(1,3),COMP,N_ALL(1,3)       ! COMPRESS Y COORDS
*VMASK,MASK17                            ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP17(1,4),COMP,N_ALL(1,4)       ! COMPRESS Z COORDS
SORT2D,'N_TMP17',3,,,0.001               ! SORT BY Y  (0.001 SPATIAL TOLER) -MACRO

! CREATE "MASKING" MATRIX -OUTSIDE- RIGHT EDGE !

*DIM,MASK18,ARRAY,N_NUM                   ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,X,X5+0.5*DEL_F,X5+1.5*DEL_F    ! SELECT NODES EXTERIOR TO RIGHT CRACK FRONT
NSEL,R,LOC,Z,Z1                           ! SELECT NODES AT DEPTH OF DELAM
NSEL,R,LOC,Y,Y2,Y5                        ! SELECT NODES EXTERIOR TO RIGHT EDGE OF DELAM
*VGET,MASK18(1,1),NODE,,NSEL             ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -OUTSIDE- RIGHT EDGE !

*GET,RCRK_N,NODE,,COUNT                   ! GET NUMBER OF NODES IN SET
*DIM,N_TMP18,ARRAY,RCRK_N,4              ! DIMENSION ARRAY FOR RIGHT EXTERIOR NODES
*VMASK,MASK18                            ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP18(1,1),COMP,N_ALL(1,1)       ! COMPRESS NODE NUMBERS
*VMASK,MASK18                            ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP18(1,2),COMP,N_ALL(1,2)       ! COMPRESS X COORDS
*VMASK,MASK18                            ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP18(1,3),COMP,N_ALL(1,3)       ! COMPRESS Y COORDS
*VMASK,MASK18                            ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP18(1,4),COMP,N_ALL(1,4)       ! COMPRESS Z COORDS
SORT2D,'N_TMP18',3,,,0.001               ! SORT BY Y  (0.001 SPATIAL TOLER) -MACRO

! CREATE "MASKING" MATRIX -OUTSIDE- FRONT EDGE !

*DIM,MASK19,ARRAY,N_NUM                   ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,Y,Y2-1.5*DEL_F,Y2-0.5*DEL_F    ! SELECT NODES EXTERIOR TO FRONT CRACK FRONT
NSEL,R,LOC,Z,Z1                           ! SELECT NODES AT DEPTH OF DELAM
NSEL,R,LOC,X,X2,X5                        ! SELECT NODES EXTERIOR TO FRONT EDGE OF DELAM
*VGET,MASK19(1,1),NODE,,NSEL             ! STORE NODE SELECTION STATUS (MASKING)
```

```
! CREATE ARRAY OF NODES -OUTSIDE- FRONT EDGE !

*GET,FCRK_N,NODE,,COUNT             ! GET NUMBER OF NODES IN SET
*DIM,N_TMP19,ARRAY,FCRK_N,4         ! DIMENSION ARRAY FOR FRONT EXTERIOR NODES
*VMASK,MASK19                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP19(1,1),COMP,N_ALL(1,1)  ! COMPRESS NODE NUMBERS
*VMASK,MASK19                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP19(1,2),COMP,N_ALL(1,2)  ! COMPRESS X COORDS
*VMASK,MASK19                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP19(1,3),COMP,N_ALL(1,3)  ! COMPRESS Y COORDS
*VMASK,MASK19                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP19(1,4),COMP,N_ALL(1,4)  ! COMPRESS Z COORDS
SORT2D,'N_TMP19',2,,,0.001          ! SORT BY X  (0.001 SPATIAL TOLER) -MACRO

! CREATE "MASKING" MATRIX -OUTSIDE- BACK EDGE !

*DIM,MASK20,ARRAY,N_NUM                   ! DIMENSION ARRAY FOR SELECTION STATUS
NSEL,S,LOC,Y,Y5+0.5*DEL_F,Y5+1.5*DEL_F    ! SELECT NODES EXTERIOR TO BACK CRACK FRONT
NSEL,R,LOC,Z,Z1                           ! SELECT NODES AT DEPTH OF DELAM
NSEL,R,LOC,X,X2,X5                        ! SELECT NODES EXTERIOR TO BACK EDGE OF DELAM
*VGET,MASK20(1,1),NODE,,NSEL             ! STORE NODE SELECTION STATUS (MASKING)

! CREATE ARRAY OF NODES -OUTSIDE- BACK EDGE !

*GET,BCRK_N,NODE,,COUNT             ! GET NUMBER OF NODES IN SET
*DIM,N_TMP20,ARRAY,BCRK_N,4         ! DIMENSION ARRAY FOR BACK EXTERIOR NODES
*VMASK,MASK20                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP20(1,1),COMP,N_ALL(1,1)  ! COMPRESS NODE NUMBERS
*VMASK,MASK20                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP20(1,2),COMP,N_ALL(1,2)  ! COMPRESS X COORDS
*VMASK,MASK20                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP20(1,3),COMP,N_ALL(1,3)  ! COMPRESS Y COORDS
*VMASK,MASK20                       ! VECTOR OF NODE SELECTION STATUS
*VFUN,N_TMP20(1,4),COMP,N_ALL(1,4)  ! COMPRESS Z COORDS
SORT2D,'N_TMP20',2,,,0.001          ! SORT BY X  (0.001 SPATIAL TOLER) -MACRO

FINISH

/POST1

*DIM,L_GI,ARRAY,LCRK_N-2                  ! DIM ARRAYS FOR LEFT EDGE (AVOID CRNRS)
*DIM,L_GII,ARRAY,LCRK_N-2
*DIM,L_GT,ARRAY,LCRK_N-2
*DIM,L_GRAT,ARRAY,LCRK_N-2
HEADERSERR,FNAME(1,1),'NODE','GI','GII','GT','GRAT'
*DO,YY,1,LCRK_N-2
   B1=N_TMP5(YY+1,3)-N_TMP5(YY,3)         ! WIDTH OF ELEM (I-1 TO I)
   B2=N_TMP5(YY+2,3)-N_TMP5(YY+1,3)       ! WIDTH OF ELEM (I TO I+1)
   A1=N_TMP13(YY*2,2)-N_TMP5(YY+1,2)      ! LENGTH OF ELEM INSIDE CRACK
   A2=N_TMP5(YY+1,2)-N_TMP17(YY+1,2)      ! LENGTH OF ELEM OUTSIDE CRACK
   ! MODE I SERR ! (J/m^2)
   L_GI(YY)=abs(0.5*1/(0.5*A1*B1+0.5*A1*B2)*L_ZI(YY)*(L_WL(YY)-L_WLS(YY))*A2/A1)*1000   !
   ! MODE II SERR ! (J/m^2)
   L_GII(YY)=abs(0.5*1/(0.5*A1*B1+0.5*A1*B2)*L_XI(YY)*(L_UL(YY)-L_ULS(YY))*A2/A1)*1000  !
   L_GT(YY)=L_GI(YY)+L_GII(YY)            ! TOTAL SERR
   L_GRAT(YY)=L_GII(YY)/L_GT(YY)          ! GII TO GT RATIO
   ! WRITE DATA TO FILE [MACRO] !

APPENSERR,FNAME(1,1),N_TMP5(YY+1,1,1),L_GI(YY,1,1),L_GII(YY,1,1),L_GT(YY,1,1),L_GRAT(YY,1
,1)
*ENDDO
```

```
*DIM,R_GI,ARRAY,RCRK_N-2                  ! DIM ARRAYS FOR RIGHT EDGE (AVOID CRNRS)
*DIM,R_GII,ARRAY,RCRK_N-2
*DIM,R_GT,ARRAY,RCRK_N-2
*DIM,R_GRAT,ARRAY,RCRK_N-2
HEADERSERR,FNAME(1,2),'NODE','GI','GII','GT','GRAT'
*DO,YY,1,RCRK_N-2
   B1=N_TMP7(YY+1,3)-N_TMP7(YY,3)         ! WIDTH OF ELEM (I-1 TO I)
   B2=N_TMP7(YY+2,3)-N_TMP7(YY+1,3)       ! WIDTH OF ELEM (I TO I+1)
   A1=N_TMP7(YY+1,2)-N_TMP14(YY*2,2)      ! LENGTH OF ELEM INSIDE CRACK
   A2=N_TMP18(YY+1,2)-N_TMP7(YY+1,2)      ! LENGTH OF ELEM OUTSIDE CRACK
   ! MODE I SERR ! (J/m^2)
   R_GI(YY)=abs(0.5*1/(0.5*A1*B1+0.5*A1*B2)*R_ZI(YY)*(R_WL(YY)-R_WLS(YY))*A2/A1)*1000   !
   ! MODE II SERR ! (J/m^2)
   R_GII(YY)=abs(0.5*1/(0.5*A1*B1+0.5*A1*B2)*R_XI(YY)*(R_UL(YY)-R_ULS(YY))*A2/A1)*1000  !
   R_GT(YY)=R_GI(YY)+R_GII(YY)            ! TOTAL SERR
   R_GRAT(YY)=R_GII(YY)/R_GT(YY)          ! GII TO GT RATIO
   ! WRITE DATA TO FILE [MACRO] !

APPENSERR,FNAME(1,2),N_TMP7(YY+1,1,1),R_GI(YY,1,1),R_GII(YY,1,1),R_GT(YY,1,1),R_GRAT(YY,1
,1)
*ENDDO

*DIM,F_GI,ARRAY,FCRK_N-2                  ! DIM ARRAYS FOR FRONT EDGE (AVOID CRNRS)
*DIM,F_GII,ARRAY,FCRK_N-2
*DIM,F_GT,ARRAY,FCRK_N-2
*DIM,F_GRAT,ARRAY,FCRK_N-2
HEADERSERR,FNAME(1,3),'NODE','GI','GII','GT','GRAT'
*DO,ZZ,1,FCRK_N-2
   B1=N_TMP9(ZZ+1,2)-N_TMP9(ZZ,2)         ! WIDTH OF ELEM (I-1 TO I)
   B2=N_TMP9(ZZ+2,2)-N_TMP9(ZZ+1,2)       ! WIDTH OF ELEM (I TO I+1)
   A1=N_TMP15(ZZ*2,3)-N_TMP9(ZZ+1,3)      ! LENGTH OF ELEM INSIDE CRACK
   A2=N_TMP9(ZZ+1,3)-N_TMP19(ZZ+1,3)      ! LENGTH OF ELEM OUTSIDE CRACK
   ! MODE I SERR ! (J/m^2)
   F_GI(ZZ)=abs(0.5*1/(0.5*A1*B1+0.5*A1*B2)*F_ZI(ZZ)*(F_WL(ZZ)-F_WLS(ZZ))*A2/A1)*1000   !
   ! MODE II SERR ! (J/m^2)
   F_GII(ZZ)=abs(0.5*1/(0.5*A1*B1+0.5*A1*B2)*F_XI(ZZ)*(F_UL(ZZ)-F_ULS(ZZ))*A2/A1)*1000  !
   F_GT(ZZ)=F_GI(ZZ)+F_GII(ZZ)            ! TOTAL SERR
   F_GRAT(ZZ)=F_GII(ZZ)/F_GT(ZZ)          ! GII TO GT RATIO
   ! WRITE DATA TO FILE [MACRO] !

APPENSERR,FNAME(1,3),N_TMP9(ZZ+1,1,1),F_GI(ZZ,1,1),F_GII(ZZ,1,1),F_GT(ZZ,1,1),F_GRAT(ZZ,1
,1)
*ENDDO

*DIM,B_GI,ARRAY,BCRK_N-2                  ! DIM ARRAYS FOR BACK EDGE (AVOID CRNRS)
*DIM,B_GII,ARRAY,BCRK_N-2
*DIM,B_GT,ARRAY,BCRK_N-2
*DIM,B_GRAT,ARRAY,BCRK_N-2
HEADERSERR,FNAME(1,4),'NODE','GI','GII','GT','GRAT'
*DO,ZZ,1,BCRK_N-2
   B1=N_TMP11(ZZ+1,2)-N_TMP11(ZZ,2) ! WIDTH OF ELEM (I-1 TO I)
   B2=N_TMP11(ZZ+2,2)-N_TMP11(ZZ+1,2)     ! WIDTH OF ELEM (I TO I+1)
   A1=N_TMP11(ZZ+1,3)-N_TMP16(ZZ*2,3)     ! LENGTH OF ELEM INSIDE CRACK
   A2=N_TMP20(ZZ+1,3)-N_TMP11(ZZ+1,3)     ! LENGTH OF ELEM OUTSIDE CRACK
   ! MODE I SERR ! (J/m^2)
   B_GI(ZZ)=abs(0.5*1/(0.5*A1*B1+0.5*A1*B2)*B_ZI(ZZ)*(B_WL(ZZ)-B_WLS(ZZ))*A2/A1)*1000   !
   ! MODE II SERR ! (J/m^2)
   B_GII(ZZ)=abs(0.5*1/(0.5*A1*B1+0.5*A1*B2)*B_XI(ZZ)*(B_UL(ZZ)-B_ULS(ZZ))*A2/A1)*1000  !
   B_GT(ZZ)=B_GI(ZZ)+B_GII(ZZ)            ! TOTAL SERR
   B_GRAT(ZZ)=B_GII(ZZ)/B_GT(ZZ)          ! GII TO GT RATIO
   ! WRITE DATA TO FILE [MACRO] !
```

```
APPENSERR,FNAME(1,4),N_TMP11(ZZ+1,1,1),B_GI(ZZ,1,1),B_GII(ZZ,1,1),B_GT(ZZ,1,1),B_GRAT(ZZ,
1,1)
*ENDDO

FINISH

!================================================================================!
!                  EVALUATE MAX STRESS FAILURE CRITERION                         !
!================================================================================!

!/POST1

!ALLSEL                            ! SELECT EVERYTHING
!LAYER,FCMAX                       ! PROCESS LAYER W/LARGEST FAILURE CRITERIA
!PRESOL,FAIL,SMAX                  ! PRINT ELEMENT MAXIMUM STRESS FC


!FINISH
```

Appendix H
Strain Rate Predictions

H1. Prediction of Sandwich Laminate Properties and Test Performance

At the beginning of this study an analysis was performed to predict the mechanical properties of the different sandwich constructions. This work was undertaken in order to be able to estimate performance of the specimens in the various tests, and to be able to determine the actuator speeds needed to obtain the target strain rates. This information was needed to identify which equipment could be used for each test, and to design test fixtures for anticipated loads and deflections.

Vectorlam laminate design and analysis software (version 791.1) from Vectorply Corporation was used to predict mechanical properties for the five different sandwich constructions. In each case the full sandwich was built in a new Vectorlam file. Separate laminates were then created for each of the sandwich facings. In some cases materials for core or reinforcements were created or cloned from similar materials if the correct material was not originally included in the software material library. For all of the laminates, an infused fiber mass fraction of 60% was assumed. Table H1 contains a summary of laminate property predictions from Vectorlam that were used in later calculations. Core shear strength and modulus properties were obtained from the manufacturer's data sheet for each core type.

Table H1: Panel property predictions from Vectorlam software

	Sandwich Construction Type				
Property	1	2	3	4	5
Sandwich thickness - mm (in.)	85.9 (3.38)	46 (1.8)	55.4 (2.18)	28 (1.1)	41.1 (1.62)
Top facing modulus - GPa (Msi)	17.7 (2.57)	18.2 (2.64)	43.1 (6.25)	43.1 (6.25)	41.9 (6.07)
Top facing thickness - mm (in.)	4.80 (0.189)	3.58 (0.141)	1.65 (0.065)	1.65 (0.065)	1.19 (0.047)
Bottom facing modulus - GPa (Msi)	17.4 (2.52)	17.7 (2.57)	26.3 (3.81)	34.0 (4.93)	21.6 (3.13)
Bottom facing thickness - mm (in.)	4.95 (0.195)	3.73 (0.147)	3.20 (0.126)	2.18 (0.086)	2.82 (0.111)
Top facing 0° ten. ult. Stress - MPa (ksi)	290 (42.1)	299 (43.3)	437 (63.4)	437 (63.4)	338 (49.0)
Top facing 0° comp. ult. stress - MPa (ksi)	335 (48.6)	345 (50.0)	367 (53.2)	367 (53.2)	239 (34.7)
Bottom facing 0° ten. ult. stress - MPa (ksi)	284 (41.2)	290 (42.1)	259 (37.6)	321 (46.5)	254 (36.8)
Bottom facing 0° comp. ult. stress - MPa (ksi)	328 (47.5)	335 (48.6)	218 (31.6)	248 (36.0)	41 (5.9)

After laminate properties were predicted, the performance of the different sandwich types in a three-point ASTM C393-06 [H1] test were investigated. A support span of at least eight times the sandwich thickness was chosen for each panel type. The specimen widths were chosen to be at least two times the sandwich thicknesses. The specimen dimensions are presented in Table H2.

Table H2: Dimensions for three-point ASTM C393-06 bending tests

	Sandwich Construction Type				
Dimension	1	2	3	4	5
Support span - mm (in.)	711 (28)	406 (16)	457 (18)	254 (10)	356 (14)
Specimen width - mm (in.)	178 (7.0)	102 (4.0)	127 (5.0)	102 (4.0)	102 (4.0)

Next, the flexural stiffness and shear rigidity were calculated for each panel type. Equations from ASTM C393-00 [H2] were used for all the calculations that follow.

Panel flexural stiffness calculation:

$$D = \frac{E_1 t_1 E_2 t_2 (d+c)^2 b}{4(E_1 t_1 + E_2 t_2)} \quad \textbf{(H1)}$$

where:

D = panel flexural stiffness - N-mm^2 (lb-in^2)

E_1 = modulus of the top facesheet- MPa (psi)

E_2 = modulus of the bottom facesheet - MPa (psi)

t_1= thickness of the top facesheet - mm (in.)

t_2= thickness of the bottom facesheet - mm (in.)

d = sandwich thickness - mm (in.)

c = core thickness - mm (in.)

b = specimen width - mm (in.)

Panel shear rigidity calculation:

$$U = \frac{G(d+c)^2 b}{4c} \quad \textbf{(H2)}$$

where:

U = panel shear rigidity - N (lb)

G = core shear modulus - MPa (psi)

d = sandwich thickness - mm (in.)

c = core thickness - mm (in.)

b = specimen width - mm (in.)

It was assumed that each specimen would fail in core shear before either facing failed due to bending stresses. The load required to fail each specimen in a quasi-static test for the selected test dimensions was calculated using Equation H3.

$$P = \tau(d+c)b \quad \textbf{(H3)}$$

where:

P = load - N (lb)

τ = core shear stress - MPa (psi)

d = sandwich thickness - mm (in.)

c = core thickness - mm (in.)

b = specimen width - mm (in.)

The total mid-span deflection at the ultimate load for each specimen was predicted using Equation H4, which includes deflection from bending and deflection from shear deformation:

$$w_{\max} = \frac{PL^3}{48D} + \frac{PL}{4U} \quad \textbf{(H4)}$$

where:

w_{max} = mid-span deflection - mm (in.)

P = load - N (lb)

L = support span - mm (in.)

D = panel bending stiffness - N-mm^2 (lb-in^2)

U = panel shear rigidity - N (lb)

The bending stress on each face of the sandwich panel was calculated for the ultimate loads using the following equation:

$$\sigma = \frac{PL}{2t(d+c)b} \quad \textbf{(H5)}$$

where:

σ = stress on face due to bending - MPa (psi)

P = load - N (lb)

L = support span - mm (in.)

t = facing thickness - mm (in.)

d = sandwich thickness - mm (in.)

c = core thickness - mm (in.)

b = specimen width - mm (in.)

In all cases the calculated stresses are well below the ultimate strengths predicted in Vectorlam. This check was done to verify the assumption that the failure mode at ultimate load will be core shear for the selected test parameters.

The results of the computations for Equations H2-H5 for each of the sandwich panel types are presented in Table H3.

Table H3: ASTM C393 test ultimate load predictions

	Sandwich Construction Type				
Property	1	2	3	4	5
Panel bending stiffness, *D* - kN-mm^2 (lb-in^2) x 10^6	49.9 (17.4)	5.88 (2.05)	14 (4.8)	2.6 (0.91)	4.39 (1.53)
Panel shear rigidity, *U* - N (lb) x10^3	766.9 (172.4)	164 (36.9)	287 (64.6)	82.7 (18.6)	123 (27.6)
Ultimate load - kN (lb)	63.43 (14260)	13.64 (3067)	19.61 (4408)	5.894 (1325)	8.781 (1974)
Total deflection at ult. load - mm (in.)	24 (0.95)	12 (0.46)	11 (0.42)	5.3 (0.21)	8.1 (0.32)
Bending stress for top face - MPa (ksi)	-163 (-23.6)	-91.0 (-13.2)	-201 (-29.2)	-84.1 (-12.2)	-162 (-23.5)
Bending stress for bottom face - MPa (ksi)	158 (22.9)	86.9 (12.6)	104 (15.1)	63 (9.2)	69 (10)

The rate of core shear strain resulting from dynamic loading needed to be predicted to understand what the required actuator displacement rates would be. As discussed in Section 3.2.4 the core shear strain rates were first computed for the case where a fixed shear stress rate of 65 MPa/s (9,427 psi/s) was induced. The method used was to first determine the load required to obtain an arbitrary small mid-span deflection of each specimen type, by using Equation H4 and solving for the load *P*. The shear stress resulting from this load was then found using Equation H3 and solving for τ. The computed stress was divided by 65 MPa/s (9,427 psi/s) to determine that time period that the deflection needs to occur in to meet the stress rate target. This deflection rate is the required actuator speed. Finally, the core shear strain rate is related to the core shear stress rate using Equation H6:

$$\gamma = \frac{\tau_c}{G_c} \qquad \textbf{(H6)}$$

where:

γ = shear strain in the core

τ_c = shear stress in the core - MPa (psi)

G_c = shear modulus of the core - MPa (psi)

A similar method was used to determine the actuator speeds required to meet the strain rate targets established for the ASTM C393 testing, except that the time period calculation was based on the shear strain instead of the shear stress.

H2. The MATLAB code for determining actuator speed from strain rate

```
function [delta_dot_ave, delta_dot_max] = ...
    three_point_bend_deflection_rate(b,L,t,E,G,straindot)
% [delta_dot_ave, delta_dot_max] =
%   three_point_bend_deflection_rate(b,L,t,E,G,straindot)
% This function calculates the deflection rate needed to achieve a
% specified core shear strain rate
% Inputs:
%       b = width of section [in]
%       L = length of beam [in]
%       t = vector of thicknesses in the form [t_topskin, t_core,
%           t_bottomskin] [in]
%       E = elastic modului of the layers in the form [E_topskin, E_core,
%           E_bottomskin] [psi]
%       G = shear modulus of the core [psi]
%       straindot = target shear strain rate [1/s]
%
% Calculated Values:
%       EI = moment of inerta of the section [lb-in^2]
%       EQ = first moment of the area above the point of interest, about
%           the neurtral axis [lb-in]
%       Pdot_max = load rate calculated using the maxumum shear stress
%           equation [lb/s]
%       Pdot_ave = load rate calculated using the avearge shear stress
%           equation [lb/s]
%       D = bending stiffness of the section [lb-in^2]
%       U = shear ridgidity of the section [lb]
%
% Outputs:
%       delta_dot_ave = deflection rate calculated using the average shear
%           stress equation [in/s]
%       delta_dot_max = deflection rate calculated using the maxumum shear
%           stress equation [in/s]

% Calculate EI and EQ
[EI, EQ] = section_properties(b,t,E);

% Calculate load rate using max shear stress
Pdot_max = 2*straindot*EI*b*G/EQ;

% Calculate the load rate using average shear stress
Pdot_ave = 2*straindot*b*sum(t)*G;

% Calculate D and U for the deflection equation
D = (E(1)*t(1)*E(3)*t(3)*b*(sum(t) + t(2))^2)/(4*(E(1)*t(1) + E(3)*t(3)));
U = (G*b*(sum(t)+t(2))^2)/(4*t(2));

% Calculate the deflection rate using max shear stress
delta_dot_max = (Pdot_max*L^3)/(48*D) + (Pdot_max*L)/(4*U);

% Calculate the deflection rate using average shear stress
delta_dot_ave = (Pdot_ave*L^3)/(48*D) + (Pdot_ave*L)/(4*U);
```

```
function [EI, EQ] = section_properties(b,t,E)
% [EI, EQ] = section_properties(b,t,E)
% This function calculates the section properties EI and EQ
% Inputs:
%       b = width of section [in]
%       t = vector of thicknesses in the form [t_topskin, t_core,
%           t_bottomskin] [in]
%       E = elastic modului of the layers in the form [E_topskin, E_core,
%           E_bottomskin] [psi]
%
% Calculated Values:
%       h = distance from the top of the section to the neutral axis [in]
%
% Outputs:
%       EI = moment of inertia of the section [lb-in^2]
%       EQ = first moment of the area above the point of interest, about
%       the neurtral axis [lb-in]

% Calculate the neutral axis of the section
h = (0.5*E(1)*t(1)^2 + (t(1)+t(2)/2)*E(2)*t(2) +
(t(1)+t(2)+t(3)/2)*E(3)*t(3))...
    /(E(1)*t(1) + E(2)*t(2) + E(3)*t(3));

% Calculate the moment of inertia of the section
EI = b*((1/12)*E(2)*t(2)^3 + t(1)*E(1)*((t(1)+t(2))/2)^2 + ...
        t(3)*E(3)*((t(3)+t(2))/2)^2);

 % Calculate the first moment of the area above the point of interest about
 % the neutral axis
 EQ = E(1)*b*t(1)*(h-t(1)/2) + E(2)*b*(h-t(1))*(h-t(1)-0.5*(h-t(1)));
```

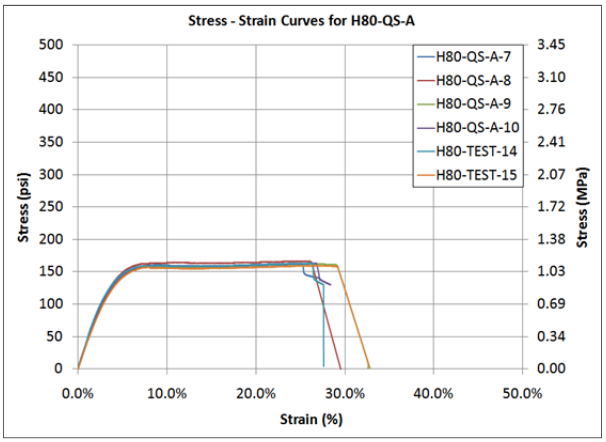
H3. References

H1. ASTM-International. (2006). ASTM C393/C393M-06 Standard Test Method for Core Shear Properties of Sandwich Constructions by Beam Flexure. West Conshohocken: ASTM-International.

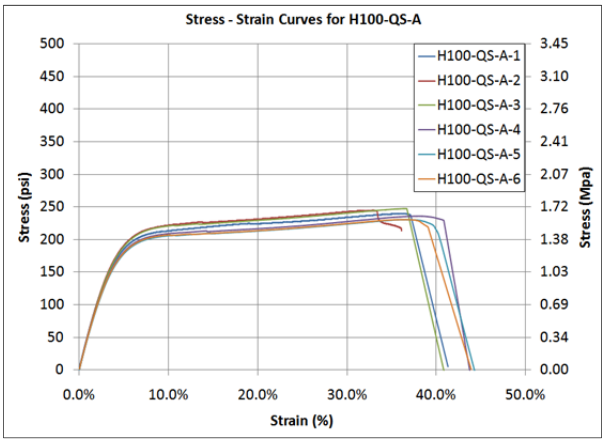
H2. ASTM-International. (2000). ASTM C393-00 Standard Test Method for Flexural Properties of Sandwich Constructions. West Conshohocken, PA: ASTM International.

Appendix I
Core Strain Rate Test Results

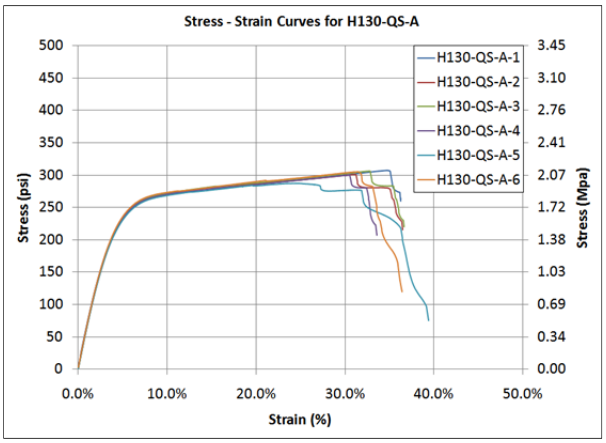
Stress-strain curves for the C273 core shear tests at 21°C (70°F):



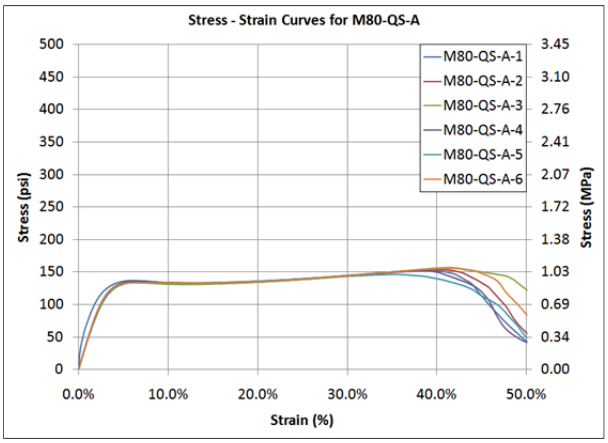
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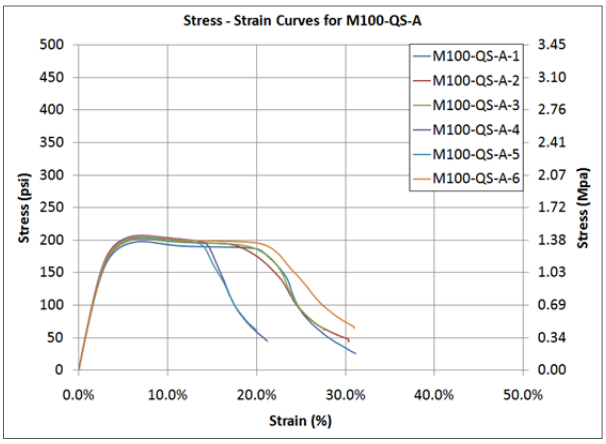
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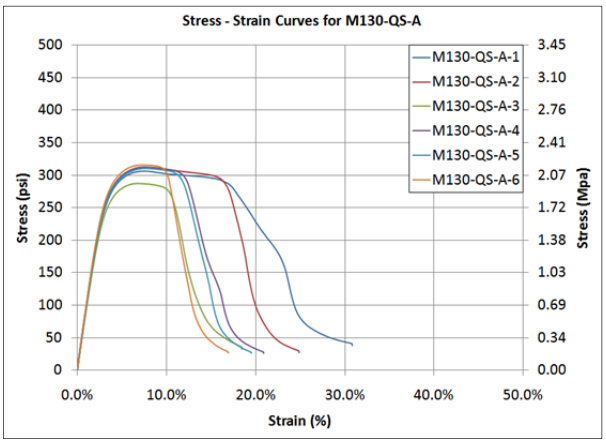
c)



d)

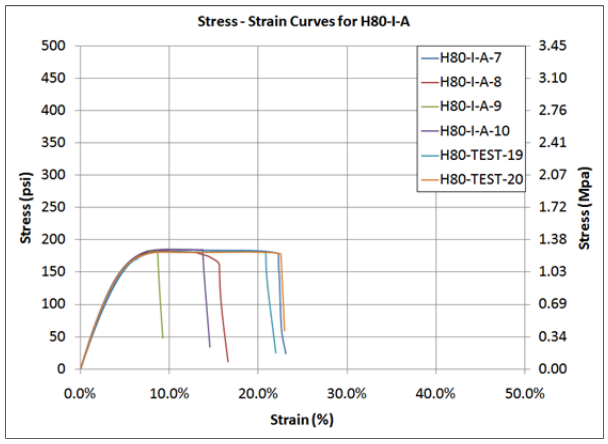


e)

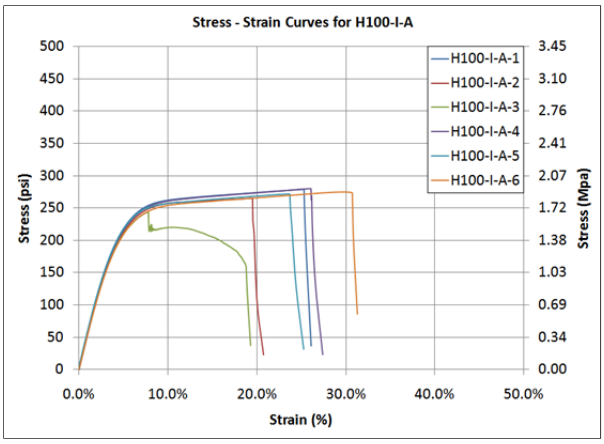


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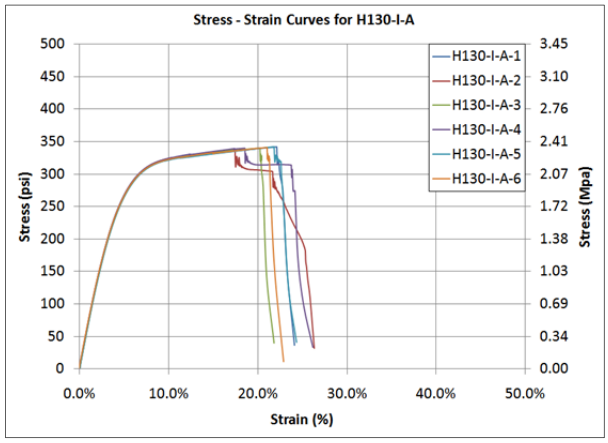
Figure I1: Stress-strain curves for the quasi-static speed, standard temperature C273 tests. a) H80 foam, b) H100 foam, c) H130 foam, d) M80 foam, e) M100 foam, f) M130 foam.



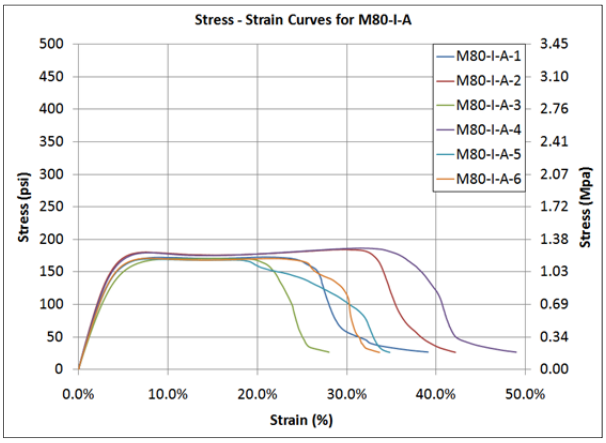
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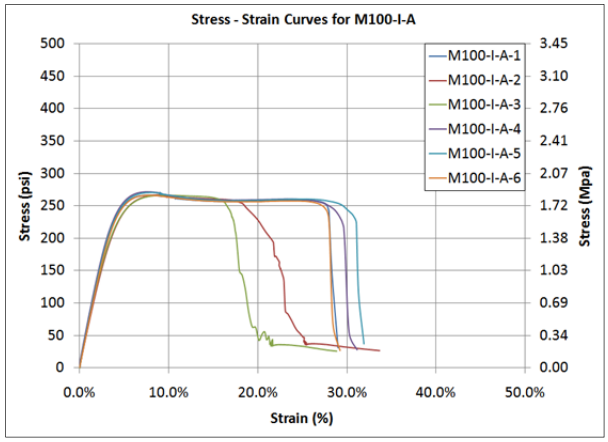
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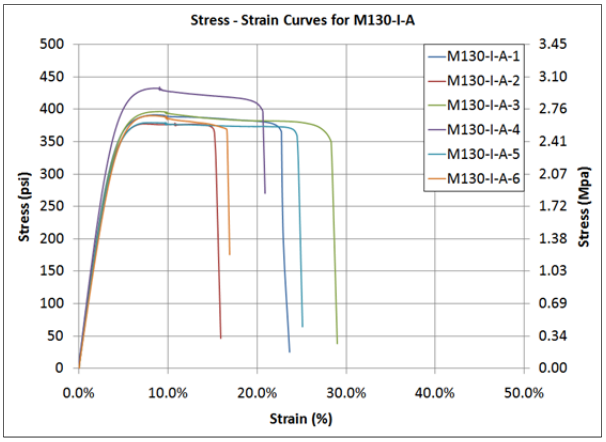
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d)

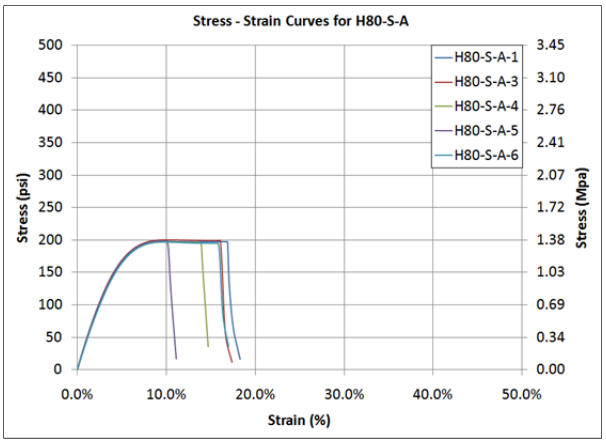


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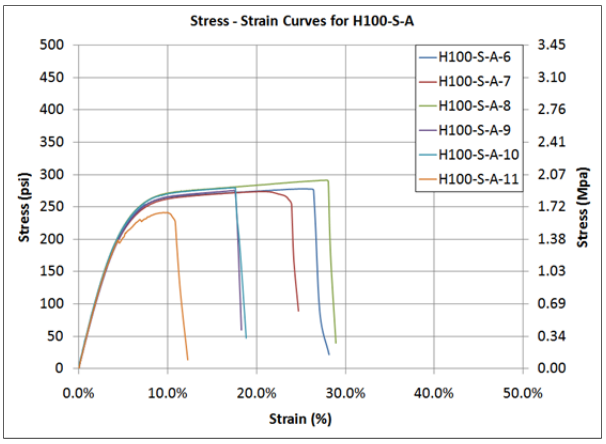


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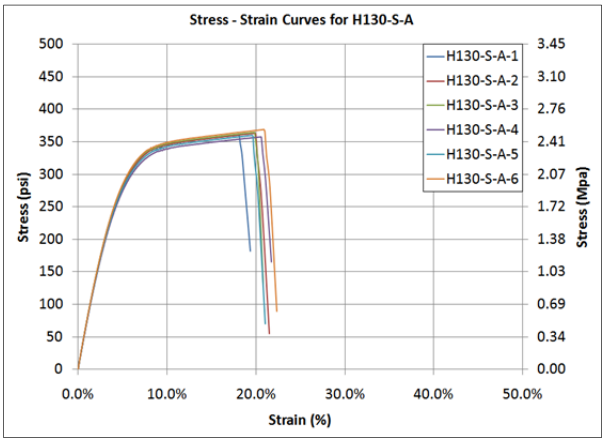
Figure I2: Stress-strain curves for the intermediate speed, standard temperature C273 tests. a) H80 foam, b) H100 foam, c) H130 foam, d) M80 foam, e) M100 foam, f) M130 foam.



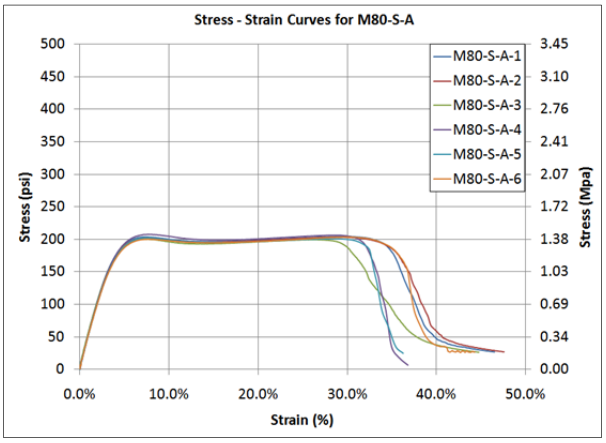
a)



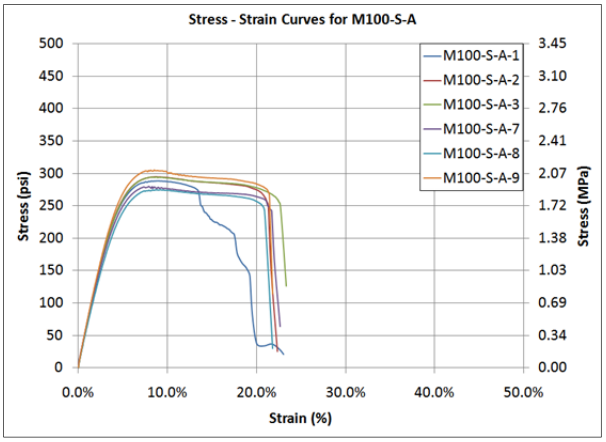
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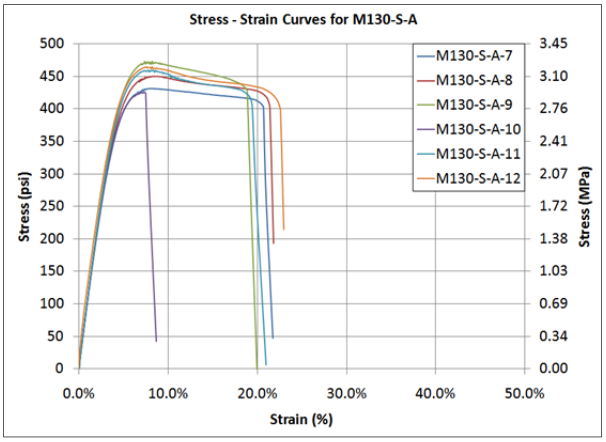
c)



d)



e)



f)

Figure I3: Stress-strain curves for the slamming speed, standard temperature C273 tests. a) H80 foam, b) H100 foam, c) H130 foam, d) M80 foam, e) M100 foam, f) M130 foam.

The results of the standard temperature C273 tests:

Table I1a: Standard Temperature (21°C), Quasi-Static Speed (SI units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (MPa)	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
H80	6	28.83	0.8608	2.99	1.121	0.01614	1.44	1.031	0.01761	1.71
H100	6	37.24	1.045	2.81	1.643	0.04954	3.01	1.319	0.04091	3.10
H130	5	46.62	0.4421	0.95	2.067	0.05326	2.58	1.674	0.01464	0.87
M80	5	32.02	0.7844	2.45	1.057	0.02976	2.82	0.9097	0.008770	0.96
M100	6	46.46	0.9727	2.09	1.404	0.02410	1.72	1.355	0.02463	1.82
M130	5	67.16	1.534	2.28	2.147	0.02434	1.13	2.066	0.02520	1.22

Table I1b: Standard Temperature (70°F), Quasi-Static Speed (English units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (psi)	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
H80	6	4182	124.8	2.99	162.6	2.342	1.44	149.5	2.555	1.71
H100	6	5401	151.6	2.81	238.3	7.186	3.01	191.3	5.934	3.10
H130	5	6762	64.12	0.95	299.8	7.725	2.58	242.9	2.123	0.87
M80	5	4644	113.8	2.45	153.3	4.316	2.82	131.9	1.272	0.96
M100	6	6739	141.1	2.09	203.7	3.496	1.72	196.5	3.572	1.82
M130	5	9741	222.5	2.28	311.4	3.531	1.13	299.7	3.654	1.22

Table I2a: Standard Temperature (21°C), Intermediate Speed (SI units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (MPa)	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
H80	6	28.84	1.072	3.72	1.265	0.01233	0.97	1.180	0.01287	1.09
H100	5	39.24	0.9948	2.54	1.891	0.03990	2.11	1.610	0.01805	1.12
H130	6	49.40	0.5615	1.14	2.346	0.01587	0.68	1.996	0.005954	0.30
M80	6	32.65	2.272	6.96	1.214	0.05223	4.30	1.147	0.04523	3.94
M100	6	48.73	2.420	4.79	1.848	0.01794	0.97	1.773	0.04735	2.67
M130	6	70.12	3.169	4.52	2.723	0.1405	5.16	2.632	0.1243	4.72

Table I2b: Standard Temperature (70°F), Intermediate Speed (English units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (psi)	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
H80	6	4183	155.4	3.72	183.5	1.789	0.97	171.1	1.867	1.09
H100	5	5691	144.3	2.54	274.2	5.787	2.11	233.5	2.617	1.12
H130	6	7165	81.43	1.14	340.2	2.302	0.68	289.5	0.864	0.30
M80	6	4736	329.5	6.96	176.1	7.575	4.30	166.4	6.560	3.94
M100	6	7067	351.0	4.79	268.0	2.601	0.97	257.2	6.867	2.67
M130	6	10170	459.7	4.52	395.0	20.38	5.16	381.7	18.03	4.72

The results of the standard temperature C273 tests (cont.):

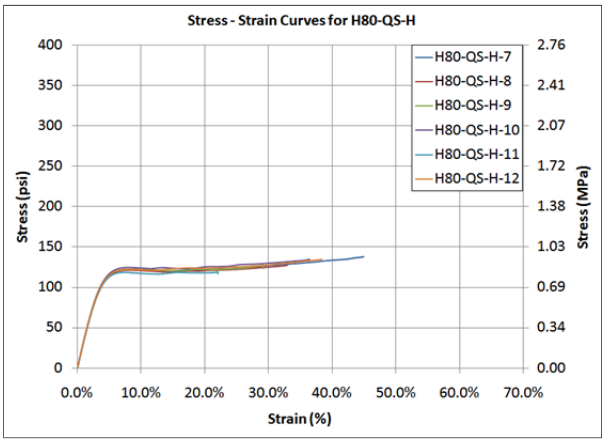
Table I3a: Standard Temperature (21°C), Slamming Speed (SI units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (MPa)	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
H80	5	31.08	1.029	3.31	1.369	0.01050	0.77	1.259	0.009022	0.72
H100	10	40.42	2.436	6.03	1.965	0.05587	2.84	1.673	0.03682	2.20
H130	6	51.63	0.9410	1.82	2.497	0.02733	1.09	2.129	0.03855	1.81
M80	6	37.14	2.537	6.83	1.405	0.01441	1.03	1.357	0.02177	1.60
M100	8	48.32	3.973	8.22	2.008	0.06737	3.36	1.929	0.07188	3.73
M130	6	77.78	7.085	9.11	3.108	0.1292	4.16	2.994	0.09644	3.22

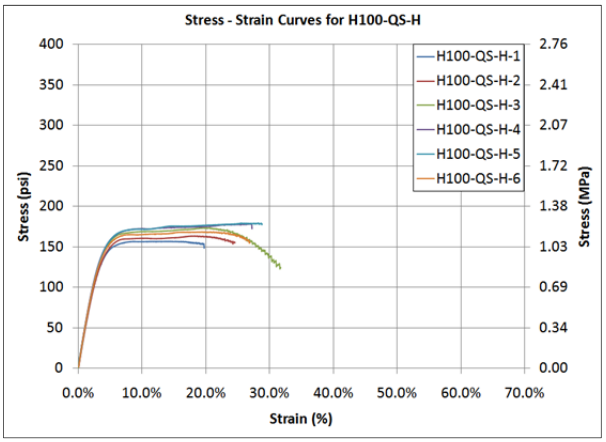
Table I3b: Standard Temperature (70°F), Slamming Speed (English units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (psi)	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
H80	5	4508	149.2	3.31	198.6	1.523	0.77	182.6	1.309	0.72
H100	10	5863	353.3	6.03	285.1	8.103	2.84	242.7	5.341	2.20
H130	6	7489	136.5	1.82	362.2	3.964	1.09	308.8	5.591	1.81
M80	6	5387	367.9	6.83	203.8	2.090	1.03	196.9	3.158	1.60
M100	8	7009	576.2	8.22	291.2	9.771	3.36	279.7	10.43	3.73
M130	6	11280	1027.6	9.11	450.8	18.74	4.16	434.3	13.99	3.22

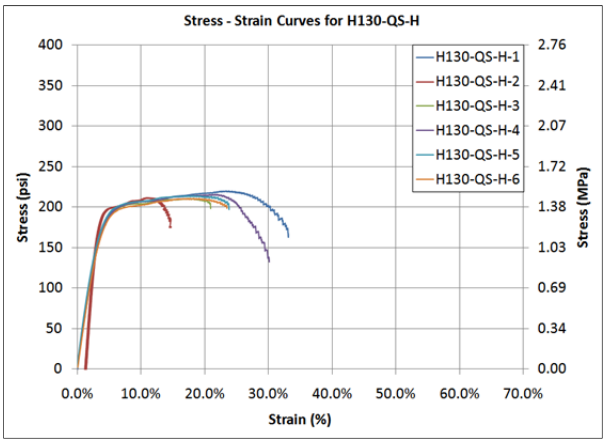
Stress-strain curves for the C273 core shear tests at 60°C (140°F):



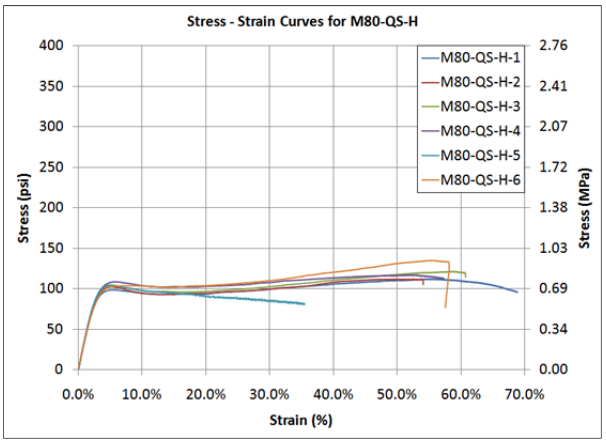
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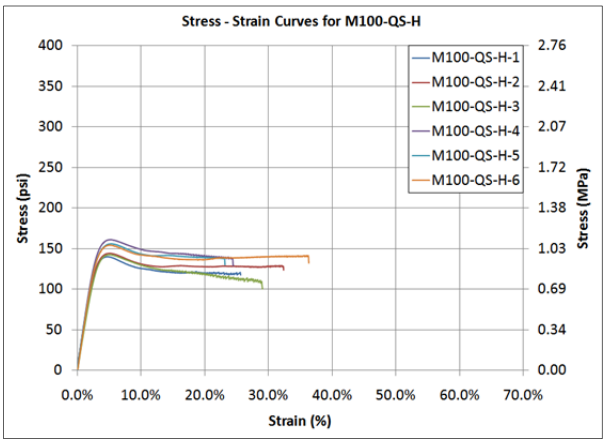
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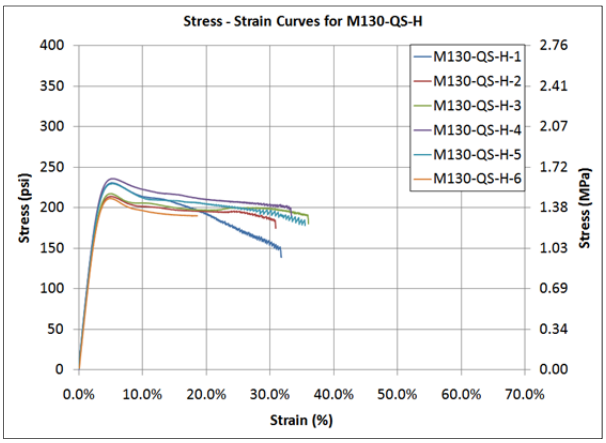
c)



d)

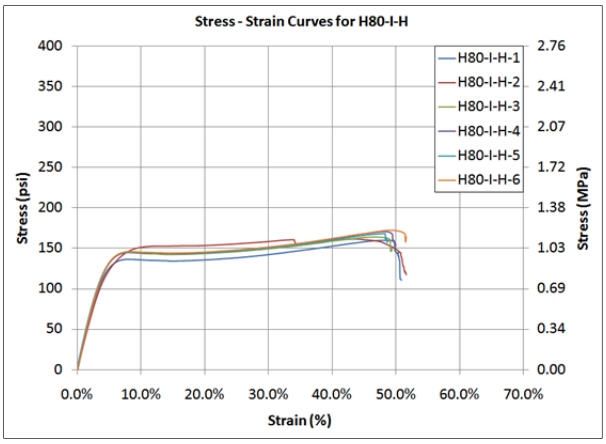


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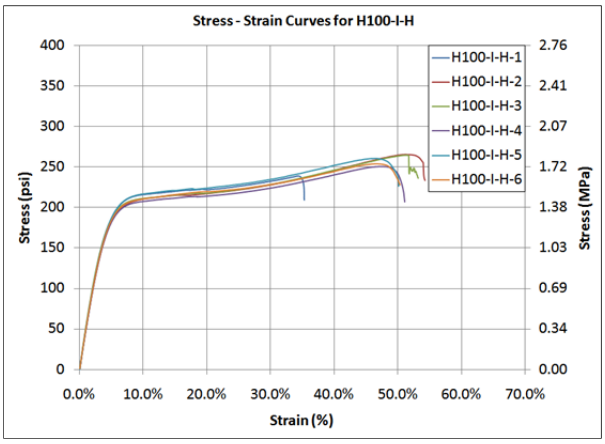


f)

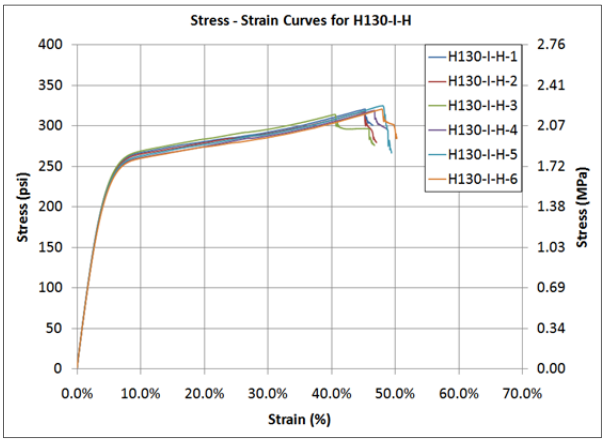
Figure I4: Stress-strain curves for the quasi-static speed, high temperature C273 tests. a) H80 foam, b) H100 foam, c) H130 foam, d) M80 foam, e) M100 foam, f) M130 foam.



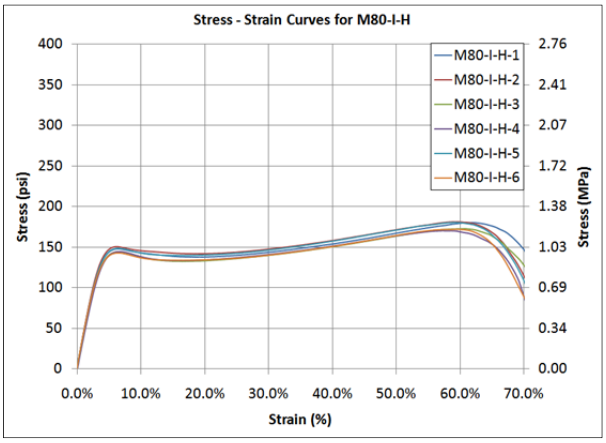
a)



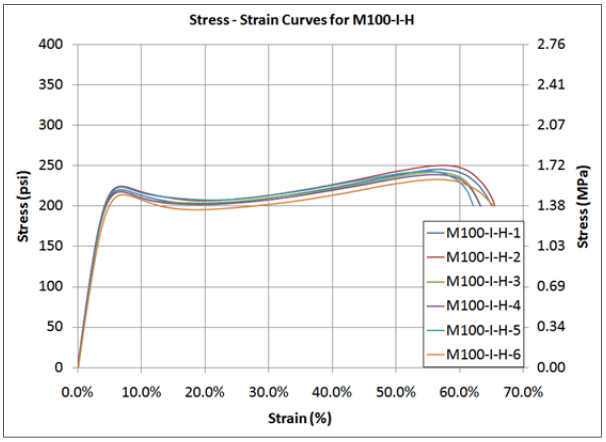
b)



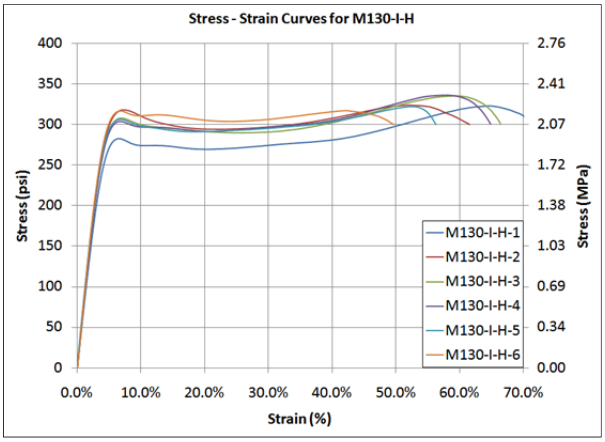
c)



d)

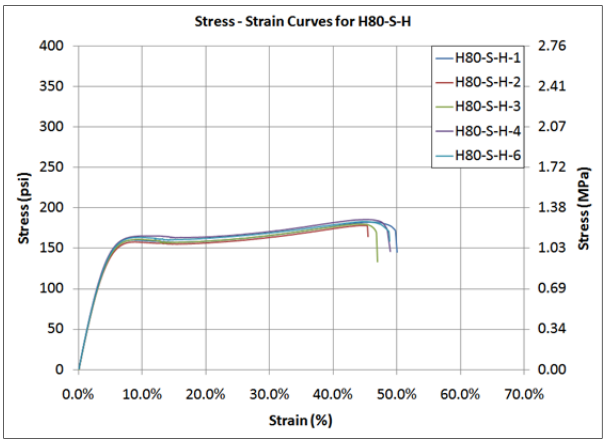


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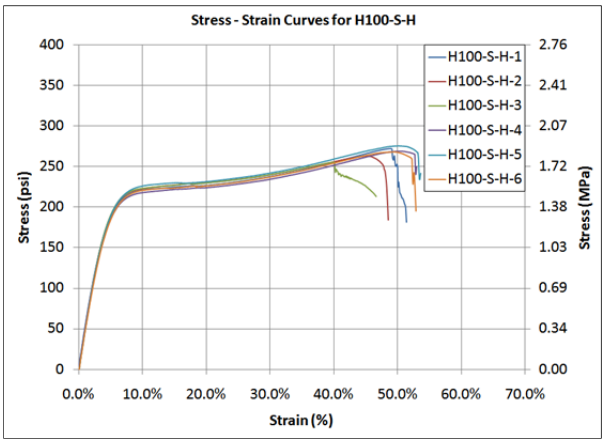


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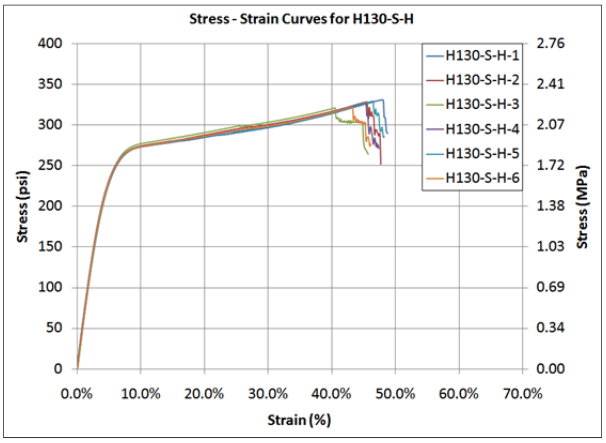
Figure I5: Stress-strain curves for the intermediate speed, high temperature C273 tests. a) H80 foam, b) H100 foam, c) H130 foam, d) M80 foam, e) M100 foam, f) M130 foam.



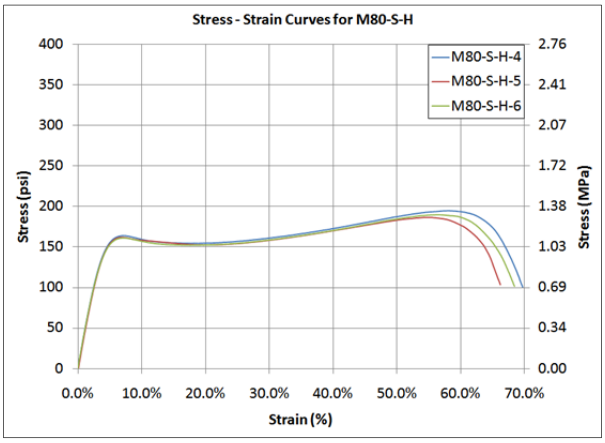
a)



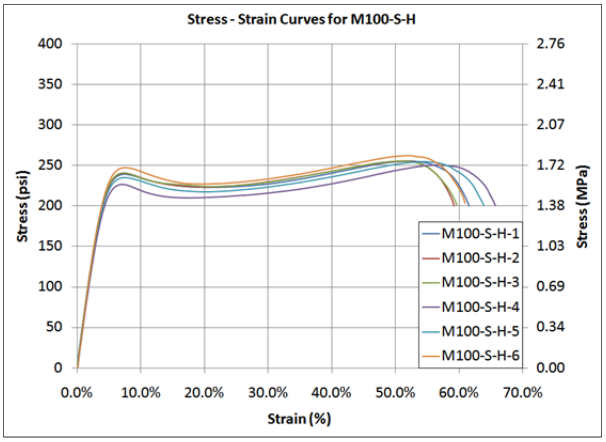
b)



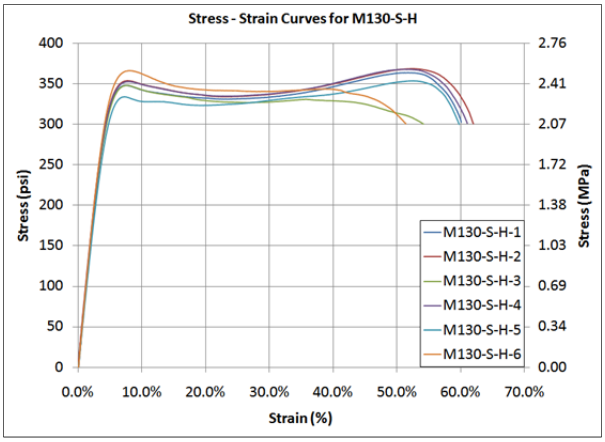
c)



d)



e)



f)

Figure I6: Stress-strain curves for the slamming speed, high temperature C273 tests. a) H80 foam, b) H100 foam, c) H130 foam, d) M80 foam, e) M100 foam, f) M130 foam.

The results of the high temperature C273 tests:

Table I4a: High Temperature (60°C), Quasi-Static Speed (SI units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (MPa)	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
H80	6	23.83	0.4044	1.70	0.8992	0.04946	5.50	0.8084	0.01105	1.37
H100	6	33.19	1.602	4.83	1.174	0.06245	5.32	1.077	0.03580	3.32
H130	5	40.06	2.870	7.17	1.477	0.02812	1.90	1.325	0.01233	0.93
M80	6	26.28	0.8539	3.25	0.8085	0.07250	8.97	0.7097	0.02389	3.37
M100	6	35.98	1.486	4.13	1.034	0.05904	5.71	1.033	0.05839	5.65
M130	6	52.44	1.552	2.96	1.539	0.06966	4.53	1.536	0.06817	4.44

Table I4b: High Temperature (140°F), Quasi-Static Speed (English units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (psi)	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
H80	6	3456	58.65	1.70	130.4	7.174	5.50	117.3	1.603	1.37
H100	6	4813	232.3	4.83	170.3	9.057	5.32	156.2	5.192	3.32
H130	5	5810	416.3	7.17	214.3	4.079	1.90	192.2	1.788	0.93
M80	6	3811	123.8	3.25	117.3	10.51	8.97	102.9	3.465	3.37
M100	6	5219	215.6	4.13	150.0	8.563	5.71	149.8	8.469	5.65
M130	6	7606	225.1	2.96	223.2	10.10	4.53	222.8	9.887	4.44

Table I5a: High Temperature (60°C), Intermediate Speed (SI units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (MPa)	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
H80	5	25.29	0.1560	0.62	1.152	0.03568	3.10	0.9474	0.02791	2.95
H100	6	35.89	0.6052	1.69	1.762	0.06966	3.95	1.343	0.02034	1.51
H130	6	42.97	0.5138	1.20	2.203	0.02580	1.17	1.668	0.02036	1.22
M80	6	29.29	0.6702	2.29	1.214	0.03421	2.82	0.9968	0.02293	2.30
M100	6	40.60	1.771	4.36	1.671	0.03950	2.36	1.494	0.02473	1.66
M130	6	54.65	2.199	4.02	2.250	0.05301	2.36	2.085	0.08116	3.89

Table I5b: High Temperature (140°F), Intermediate Speed (English units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (psi)	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
H80	5	3667	22.63	0.62	167.1	5.175	3.10	137.4	4.048	2.95
H100	6	5206	87.78	1.69	255.6	10.10	3.95	194.8	2.950	1.51
H130	6	6232	74.53	1.20	319.5	3.742	1.17	241.9	2.954	1.22
M80	6	4248	97.20	2.29	176.1	4.962	2.82	144.6	3.326	2.30
M100	6	5888	256.8	4.36	242.3	5.729	2.36	216.7	3.587	1.66
M130	6	7927	319.0	4.02	326.4	7.689	2.36	302.4	11.77	3.89

The results of the high temperature C273 tests (cont.):

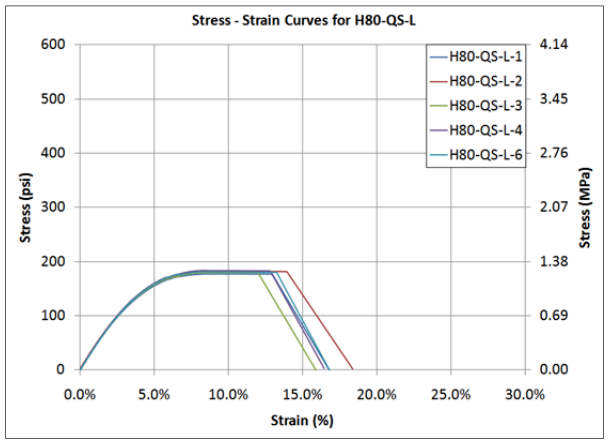
Table I6a: High Temperature (60°C), Slamming Speed (SI units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (MPa)	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
H80	5	26.67	0.6112	2.29	1.254	0.02051	1.64	1.053	0.01427	1.36
H100	6	35.18	1.154	3.28	1.842	0.04823	2.62	1.401	0.02398	1.71
H130	6	43.11	0.8903	2.07	2.251	0.02702	1.20	1.725	0.004776	0.28
M80	3	30.02	0.8628	2.87	1.312	0.02863	2.18	1.098	0.009740	0.89
M100	6	41.77	1.262	3.02	1.762	0.02540	1.44	1.611	0.04366	2.71
M130	6	58.64	1.712	2.92	2.491	0.05819	2.34	2.359	0.06334	2.68

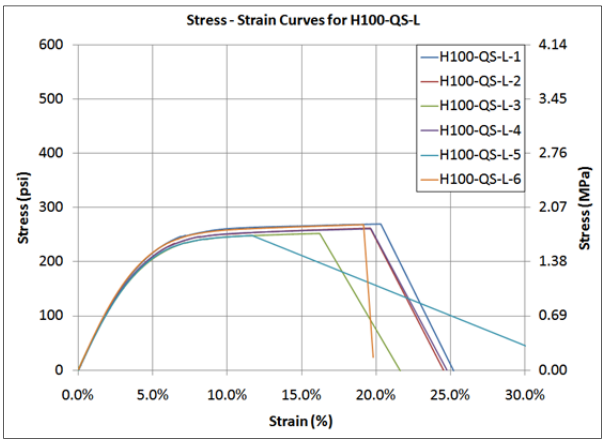
Table I6b: High Temperature (140°F), Slamming Speed (English units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (psi)	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
H80	5	3868	88.65	2.29	181.9	2.975	1.64	152.7	2.070	1.36
H100	6	5103	167.4	3.28	267.2	6.995	2.62	203.2	3.478	1.71
H130	6	6252	129.1	2.07	326.5	3.918	1.20	250.2	0.693	0.28
M80	3	4354	125.1	2.87	190.3	4.152	2.18	159.2	1.413	0.89
M100	6	6058	183.1	3.02	255.6	3.684	1.44	233.6	6.333	2.71
M130	6	8506	248.3	2.92	361.3	8.439	2.34	342.2	9.187	2.68

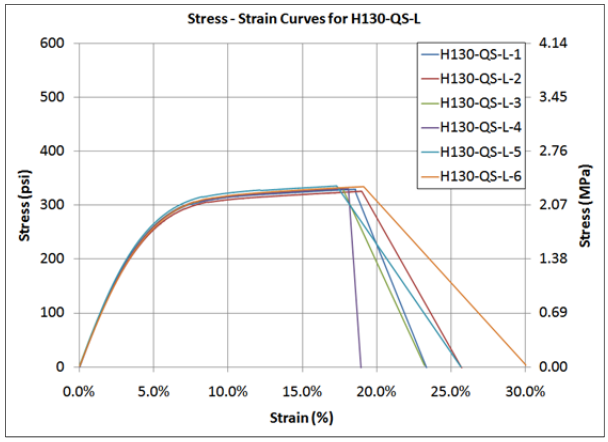
Stress-strain curves for the C273 core shear tests at -12°C (10°F):



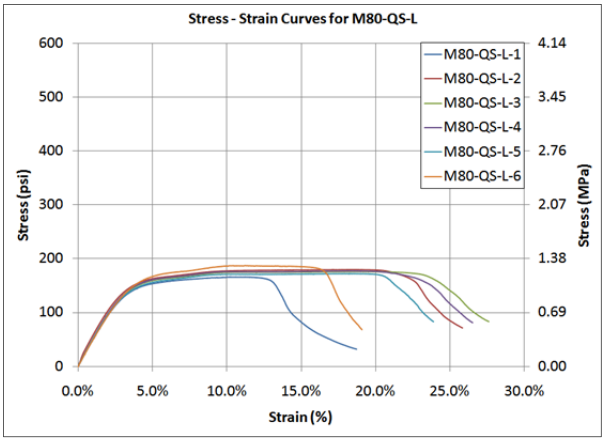
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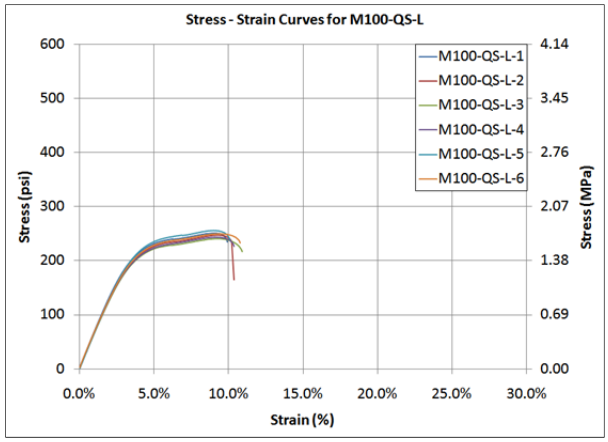
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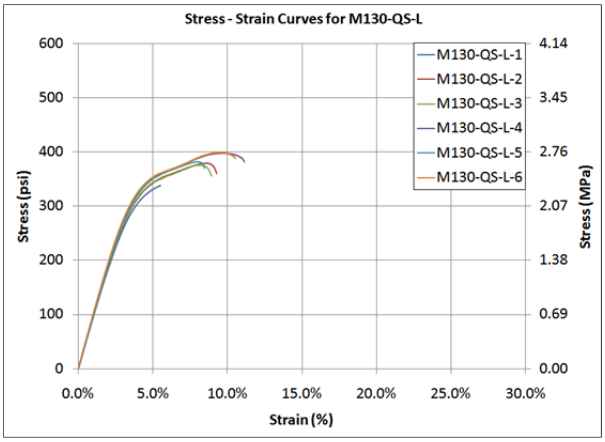
c)



d)

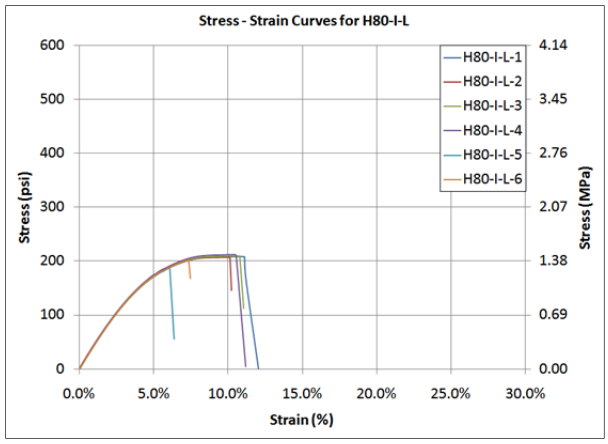


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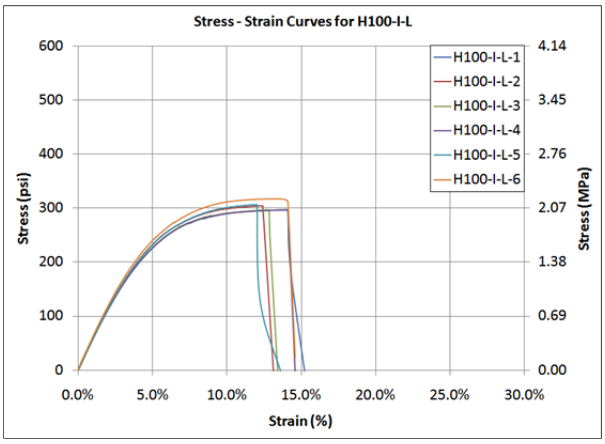


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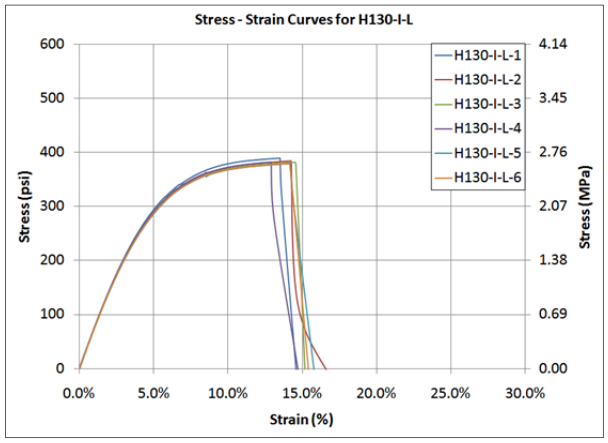
Figure I7: Stress-strain curves for the quasi-static speed, low temperature C273 tests. a) H80 foam, b) H100 foam, c) H130 foam, d) M80 foam, e) M100 foam, f) M130 foam.



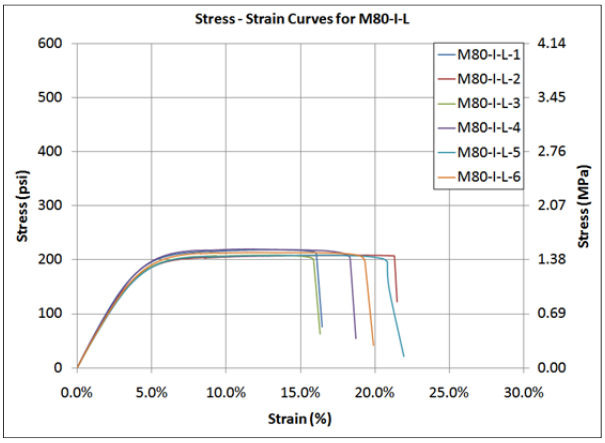
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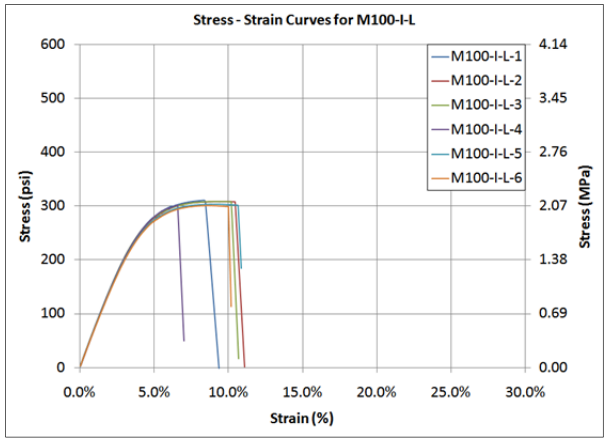
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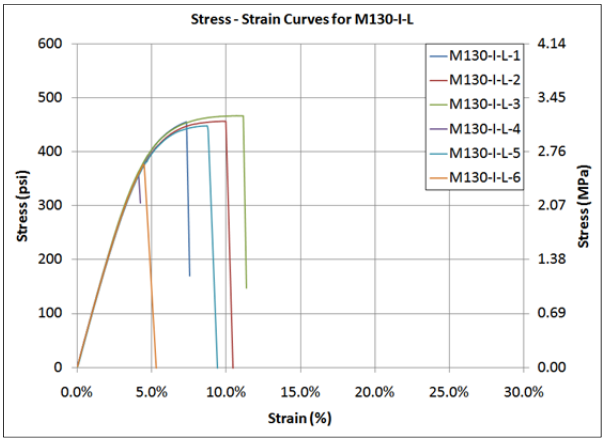
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d)

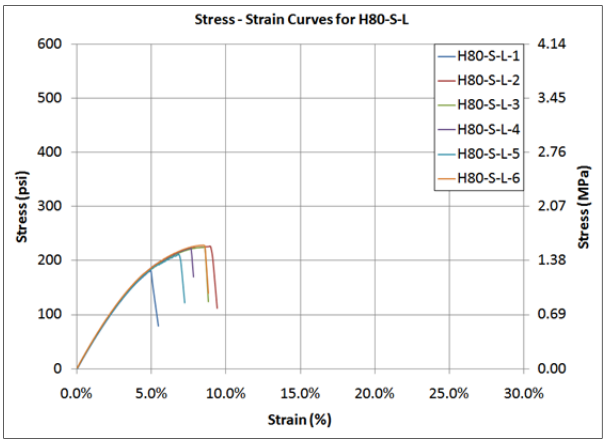


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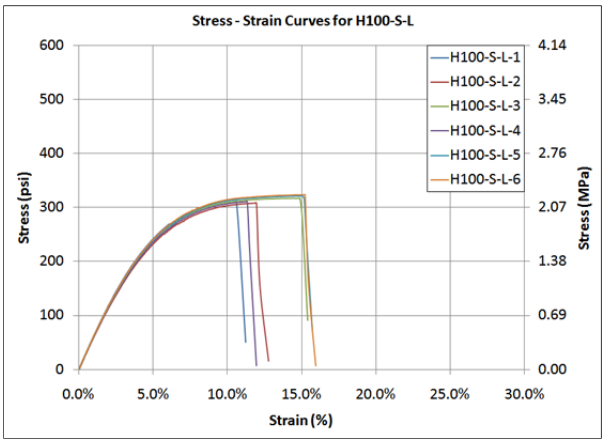


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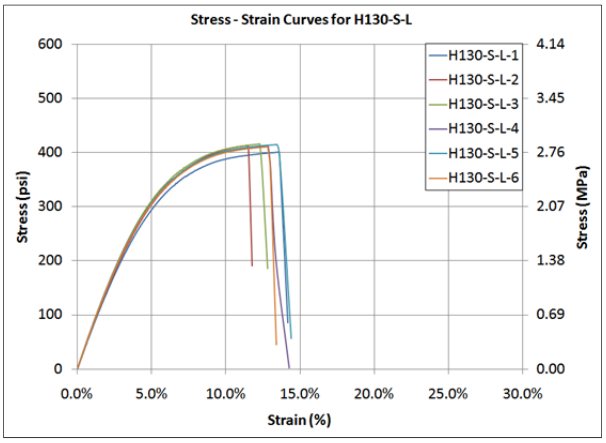
Figure I8: Stress-strain curves for the intermediate speed, low temperature C273 tests. a) H80 foam, b) H100 foam, c) H130 foam, d) M80 foam, e) M100 foam, f) M130 foam.



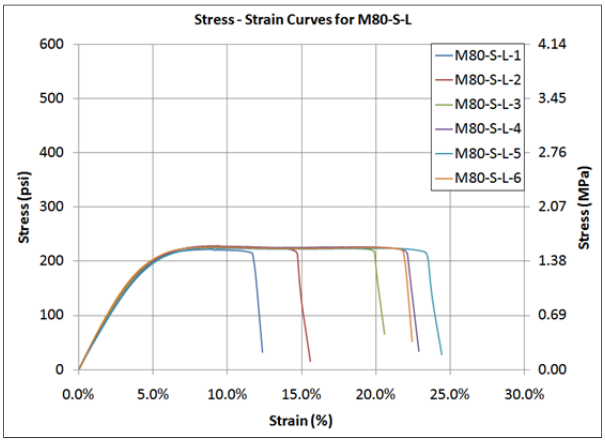
a)



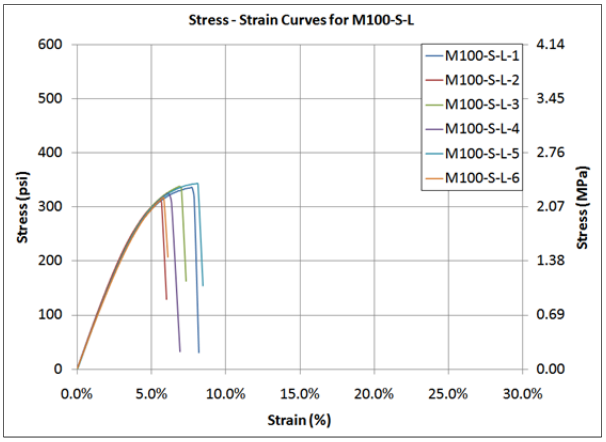
b)



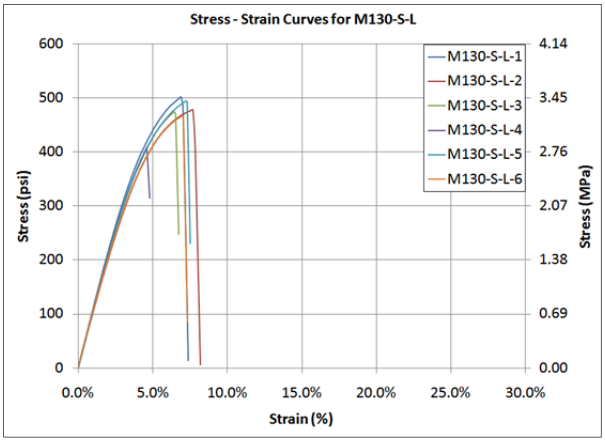
c)



d)



e)



f)

Figure I9: Stress-strain curves for the slamming speed, low temperature C273 tests. a) H80 foam, b) H100 foam, c) H130 foam, d) M80 foam, e) M100 foam, f) M130 foam.

The results of the low temperature C273 tests:

Table I7a: Low Temperature (-12°C), Quasi-Static Speed (SI units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (MPa)	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
H80	6	30.06	0.3988	1.33	1.246	0.01482	1.19	1.168	0.01116	0.95
H100	6	41.03	0.8689	2.12	1.796	0.05925	3.30	1.553	0.04080	2.63
H130	6	49.40	0.9537	1.93	2.283	0.02223	0.97	1.938	0.02217	1.14
M80	6	36.29	1.958	5.40	1.218	0.04921	4.04	1.107	0.03864	3.49
M100	6	46.85	0.8242	1.76	1.712	0.03824	2.23	1.599	0.04023	2.52
M130	5	68.15	1.320	1.94	2.670	0.07688	2.88	2.468	0.03291	1.33

Table I7b: Low Temperature (10°F), Quasi-Static Speed (English units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (psi)	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
H80	6	4360	57.84	1.33	180.8	2.150	1.19	169.4	1.618	0.95
H100	6	5952	126.0	2.12	260.4	8.594	3.30	225.3	5.918	2.63
H130	6	7164	138.3	1.93	331.2	3.224	0.97	281.1	3.215	1.14
M80	6	5264	284.0	5.40	176.6	7.138	4.04	160.6	5.605	3.49
M100	6	6795	119.5	1.76	248.4	5.546	2.23	231.9	5.835	2.52
M130	5	9884	191.4	1.94	387.2	11.15	2.88	357.9	4.774	1.33

Table I8a: Low Temperature (-12°C), Intermediate Speed (SI units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (MPa)	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
H80	5	31.12	0.2294	0.74	1.433	0.02372	1.66	1.318	0.008594	0.65
H100	6	41.63	0.6795	1.63	2.090	0.05606	2.68	1.800	0.04809	2.67
H130	6	51.94	0.6785	1.31	2.638	0.02653	1.01	2.254	0.02272	1.01
M80	6	35.91	1.117	3.11	1.469	0.03551	2.42	1.383	0.03725	2.69
M100	6	51.16	1.287	2.52	2.106	0.02858	1.36	2.019	0.02419	1.20
M130	6	70.89	1.456	2.05	3.187	0.09446	2.96	3.024	0.06915	2.29

Table I8b: Low Temperature (10°F), Intermediate Speed (English units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (psi)	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
H80	5	4513	33.28	0.74	207.8	3.441	1.66	191.1	1.246	0.65
H100	6	6038	98.56	1.63	303.1	8.131	2.68	261.1	6.974	2.67
H130	6	7534	98.41	1.31	382.6	3.847	1.01	327.0	3.296	1.01
M80	6	5208	162.0	3.11	213.1	5.151	2.42	200.6	5.402	2.69
M100	6	7420	186.7	2.52	305.5	4.145	1.36	292.9	3.508	1.20
M130	6	10280	211.2	2.05	462.2	13.70	2.96	438.6	10.03	2.29

The results of the low temperature C273 tests (cont.):

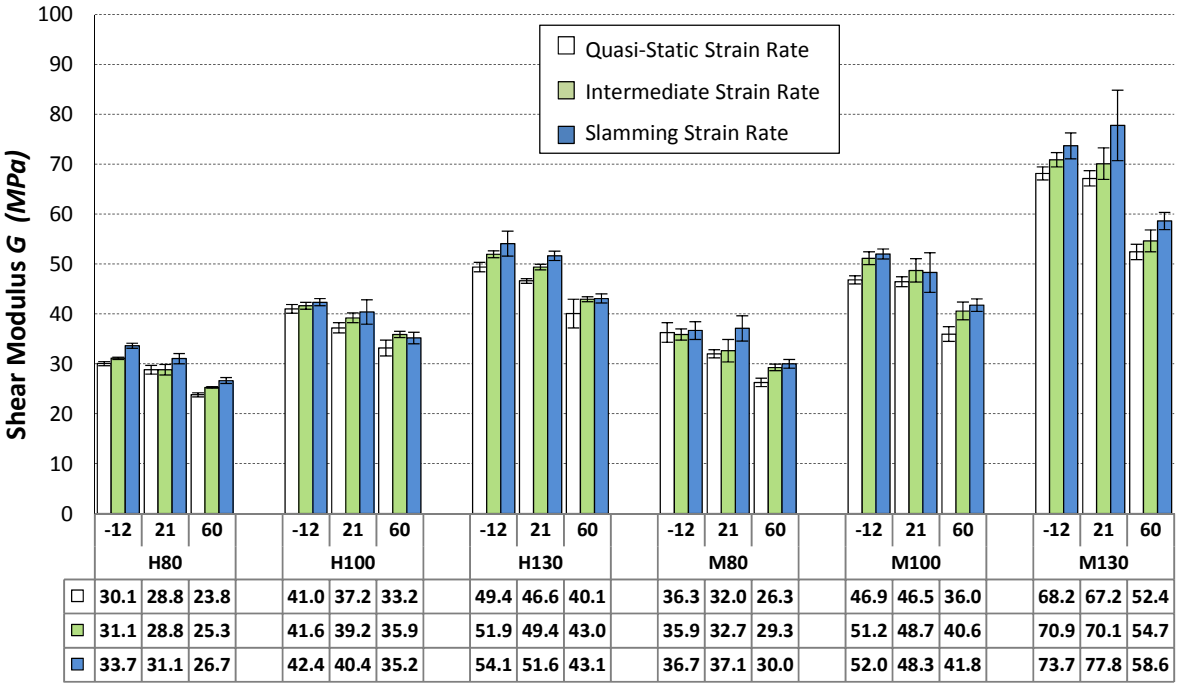
Table I9a: Low Temperature (-12°C), Slamming Speed (SI units)

Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (MPa)	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
H80	5	33.65	0.4763	1.42	1.537	0.04527	2.94	1.431	0.01096	0.77
H100	6	42.35	0.7089	1.67	2.178	0.04012	1.84	1.873	0.02492	1.33
H130	6	54.11	2.498	4.62	2.835	0.03765	1.33	2.413	0.02793	1.16
M80	6	36.69	1.799	4.90	1.558	0.01623	1.04	1.483	0.01054	0.71
M100	6	52.02	0.9938	1.91	2.349	0.02603	1.11	2.263	0.02768	1.22
M130	5	73.71	2.597	3.52	3.331	0.1010	3.03	3.256	0.09381	2.88

Table I9b: Low Temperature (10°F), Slamming Speed (English units)

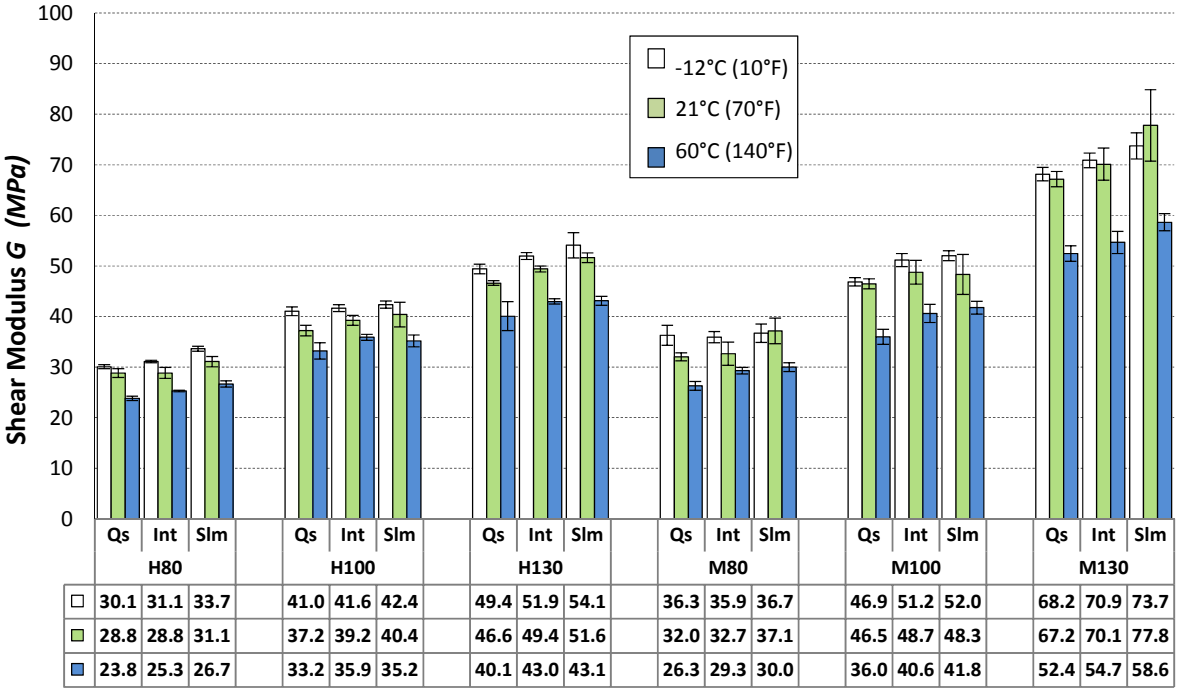
Core Type	# of Tests	G			F_{ult}			F_{off}		
		Mean (psi)	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
H80	5	4880	69.08	1.42	223.0	6.565	2.94	207.6	1.590	0.77
H100	6	6142	102.8	1.67	315.9	5.819	1.84	271.6	3.615	1.33
H130	6	7848	362.3	4.62	411.1	5.460	1.33	350.0	4.051	1.16
M80	6	5321	260.9	4.90	226.0	2.353	1.04	215.1	1.528	0.71
M100	6	7545	144.1	1.91	340.8	3.775	1.11	328.2	4.015	1.22
M130	5	10690	376.7	3.52	483.1	14.64	3.03	472.3	13.61	2.88

Plots of the C273 sandwich core shear test results:



	H80			H100			H130			M80			M100			M130		
	-12	21	60	-12	21	60	-12	21	60	-12	21	60	-12	21	60	-12	21	60
Quasi-Static Strain Rate	30.1	28.8	23.8	41.0	37.2	33.2	49.4	46.6	40.1	36.3	32.0	26.3	46.9	46.5	36.0	68.2	67.2	52.4
Intermediate Strain Rate	31.1	28.8	25.3	41.6	39.2	35.9	51.9	49.4	43.0	35.9	32.7	29.3	51.2	48.7	40.6	70.9	70.1	54.7
Slamming Strain Rate	33.7	31.1	26.7	42.4	40.4	35.2	54.1	51.6	43.1	36.7	37.1	30.0	52.0	48.3	41.8	73.7	77.8	58.6

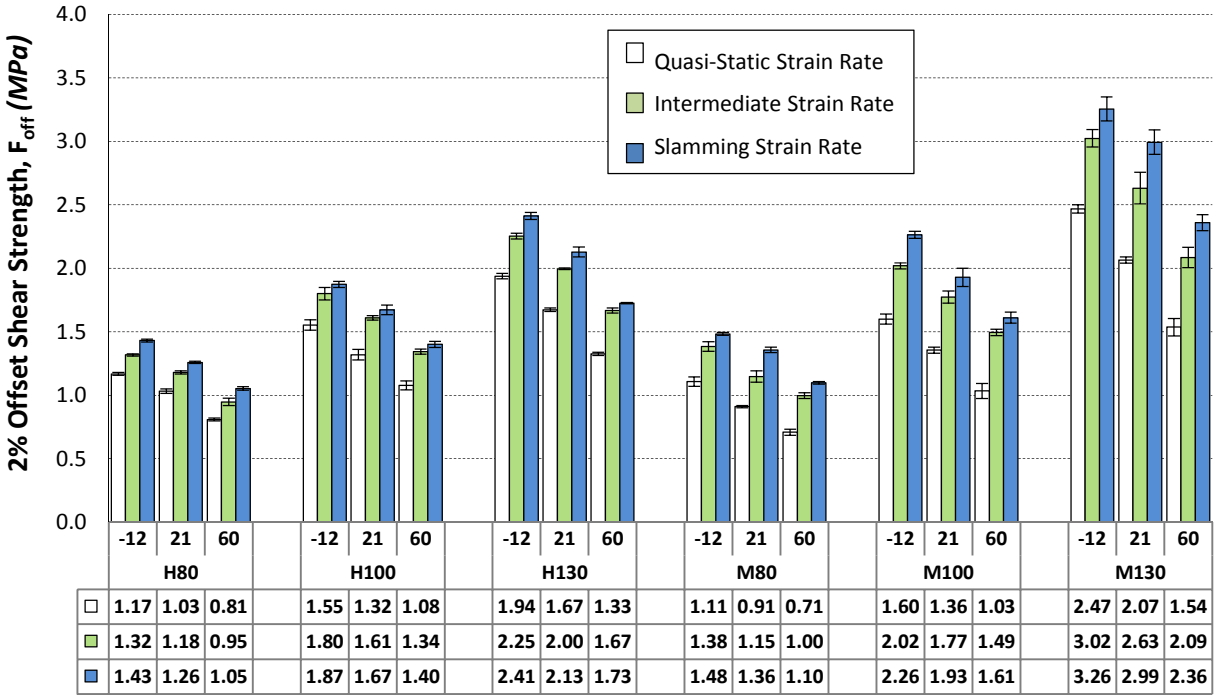
a)



	H80			H100			H130			M80			M100			M130		
	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm
-12°C (10°F)	30.1	31.1	33.7	41.0	41.6	42.4	49.4	51.9	54.1	36.3	35.9	36.7	46.9	51.2	52.0	68.2	70.9	73.7
21°C (70°F)	28.8	28.8	31.1	37.2	39.2	40.4	46.6	49.4	51.6	32.0	32.7	37.1	46.5	48.7	48.3	67.2	70.1	77.8
60°C (140°F)	23.8	25.3	26.7	33.2	35.9	35.2	40.1	43.0	43.1	26.3	29.3	30.0	36.0	40.6	41.8	52.4	54.7	58.6

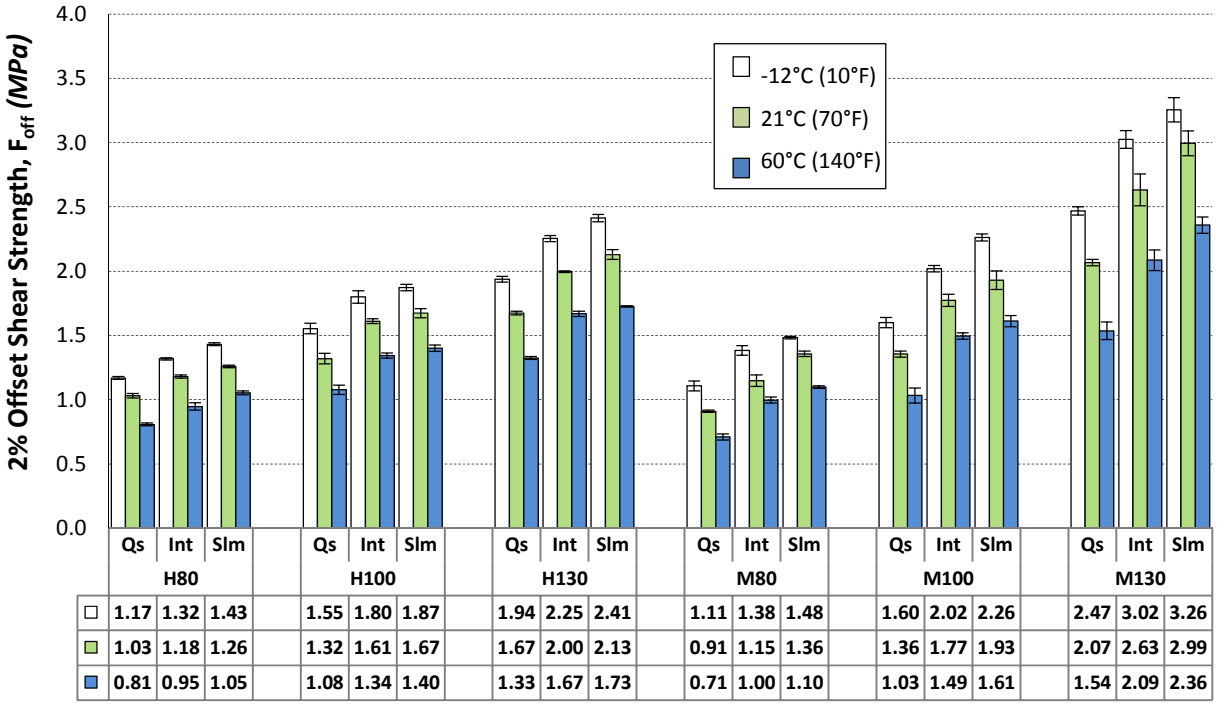
b)

Shear Modulus (*G*) results at all temperatures and strain rates grouped by core type: a) Temperature subsets, b) Strain rate subsets.



	H80			H100			H130			M80			M100			M130		
	-12	21	60	-12	21	60	-12	21	60	-12	21	60	-12	21	60	-12	21	60
Quasi-Static Strain Rate	1.17	1.03	0.81	1.55	1.32	1.08	1.94	1.67	1.33	1.11	0.91	0.71	1.60	1.36	1.03	2.47	2.07	1.54
Intermediate Strain Rate	1.32	1.18	0.95	1.80	1.61	1.34	2.25	2.00	1.67	1.38	1.15	1.00	2.02	1.77	1.49	3.02	2.63	2.09
Slamming Strain Rate	1.43	1.26	1.05	1.87	1.67	1.40	2.41	2.13	1.73	1.48	1.36	1.10	2.26	1.93	1.61	3.26	2.99	2.36

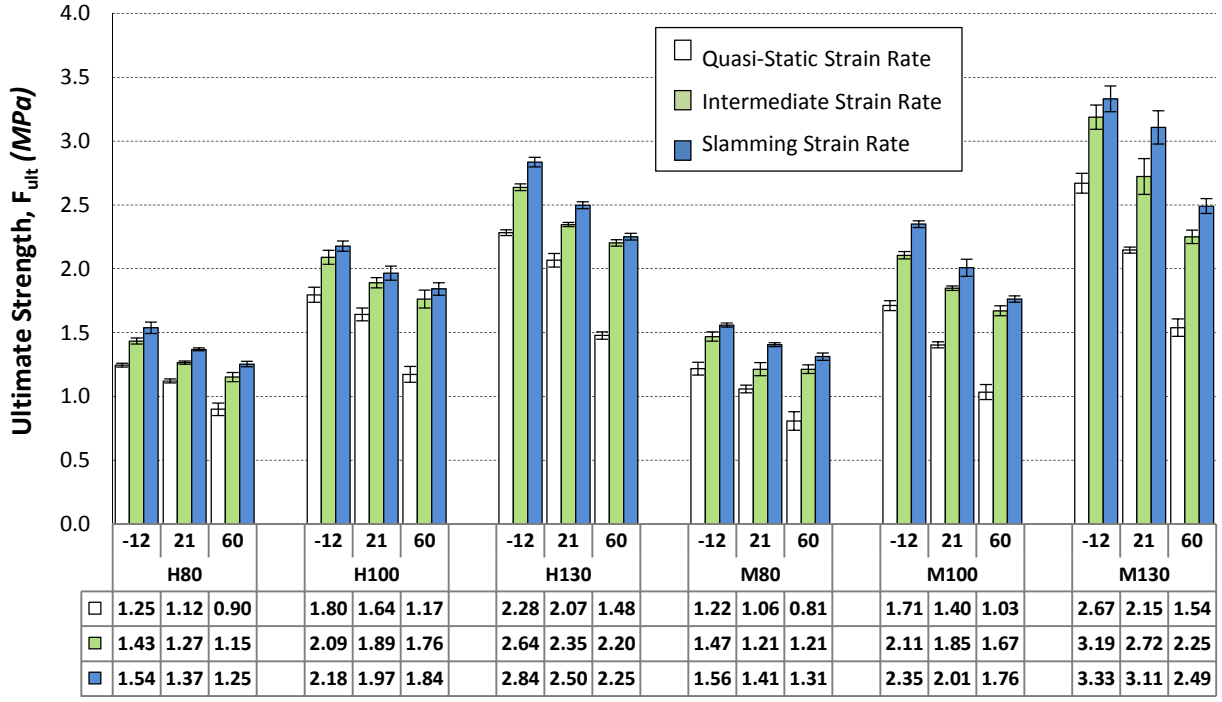
a)



	H80			H100			H130			M80			M100			M130		
	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm
-12°C (10°F)	1.17	1.32	1.43	1.55	1.80	1.87	1.94	2.25	2.41	1.11	1.38	1.48	1.60	2.02	2.26	2.47	3.02	3.26
21°C (70°F)	1.03	1.18	1.26	1.32	1.61	1.67	1.67	2.00	2.13	0.91	1.15	1.36	1.36	1.77	1.93	2.07	2.63	2.99
60°C (140°F)	0.81	0.95	1.05	1.08	1.34	1.40	1.33	1.67	1.73	0.71	1.00	1.10	1.03	1.49	1.61	1.54	2.09	2.36

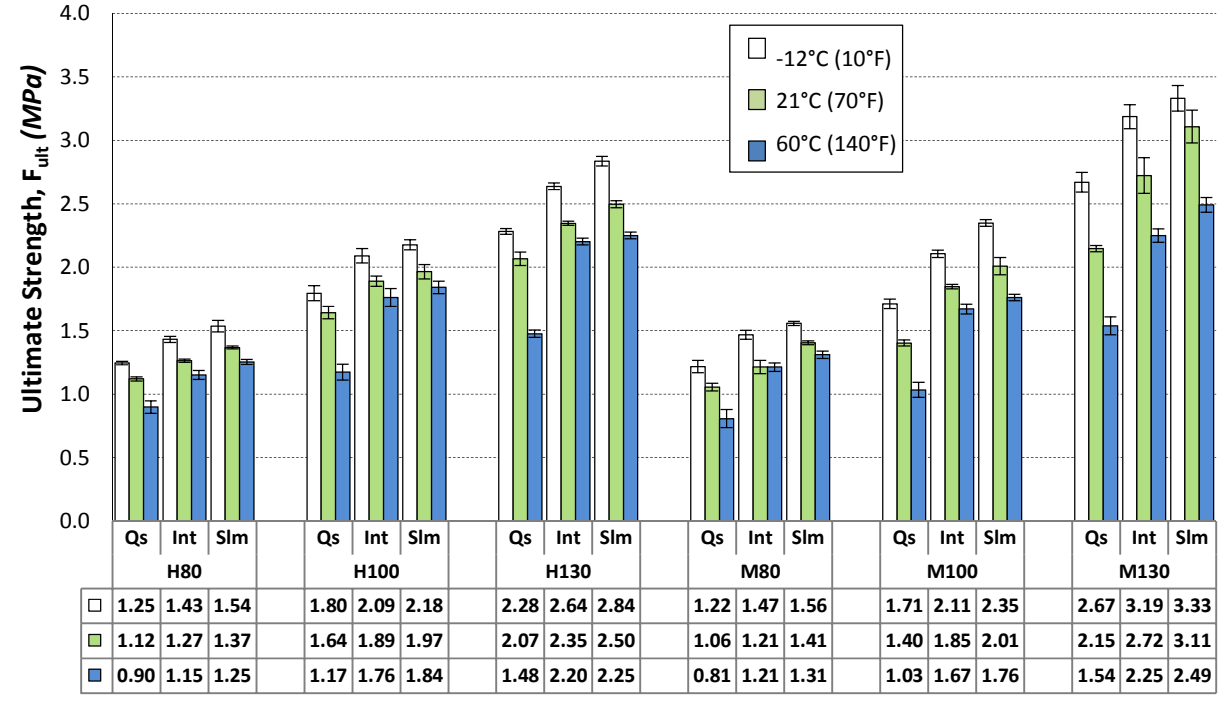
b)

2% Offset shear strength (F_{off}) results at all temperatures and strain rates grouped by core type: a) Temperature subsets, b) Strain rate subsets.



	H80			H100			H130			M80			M100			M130		
	-12	21	60	-12	21	60	-12	21	60	-12	21	60	-12	21	60	-12	21	60
Quasi-Static Strain Rate	1.25	1.12	0.90	1.80	1.64	1.17	2.28	2.07	1.48	1.22	1.06	0.81	1.71	1.40	1.03	2.67	2.15	1.54
Intermediate Strain Rate	1.43	1.27	1.15	2.09	1.89	1.76	2.64	2.35	2.20	1.47	1.21	1.21	2.11	1.85	1.67	3.19	2.72	2.25
Slamming Strain Rate	1.54	1.37	1.25	2.18	1.97	1.84	2.84	2.50	2.25	1.56	1.41	1.31	2.35	2.01	1.76	3.33	3.11	2.49

a)

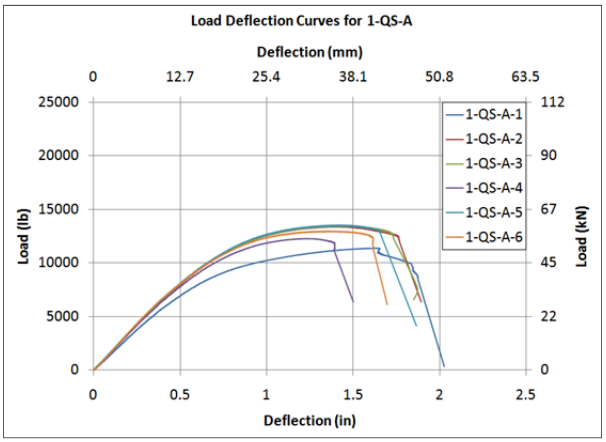


	H80			H100			H130			M80			M100			M130		
	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm
-12°C (10°F)	1.25	1.43	1.54	1.80	2.09	2.18	2.28	2.64	2.84	1.22	1.47	1.56	1.71	2.11	2.35	2.67	3.19	3.33
21°C (70°F)	1.12	1.27	1.37	1.64	1.89	1.97	2.07	2.35	2.50	1.06	1.21	1.41	1.40	1.85	2.01	2.15	2.72	3.11
60°C (140°F)	0.90	1.15	1.25	1.17	1.76	1.84	1.48	2.20	2.25	0.81	1.21	1.31	1.03	1.67	1.76	1.54	2.25	2.49

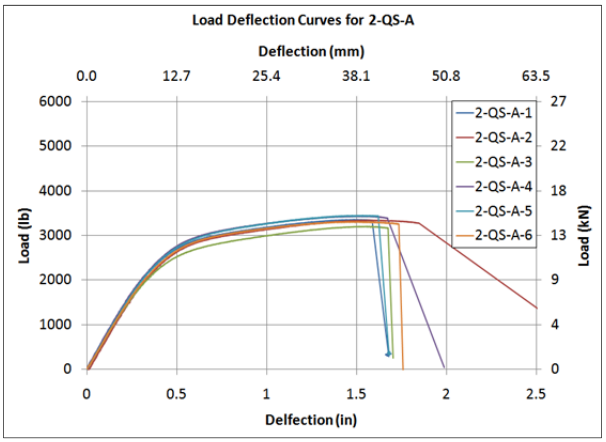
b)

Ultimate strength (F_{ult}) results at all temperatures and strain rates grouped by core type: a) Temperature subsets, b) Strain rate subsets.

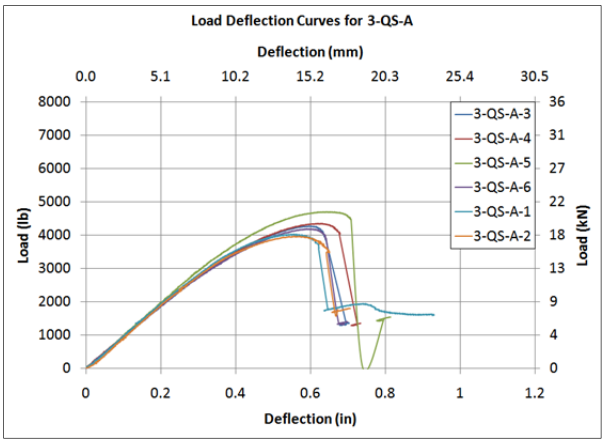
Load-deflection curves for C393 sandwich flexure tests at 21°C (70°F):



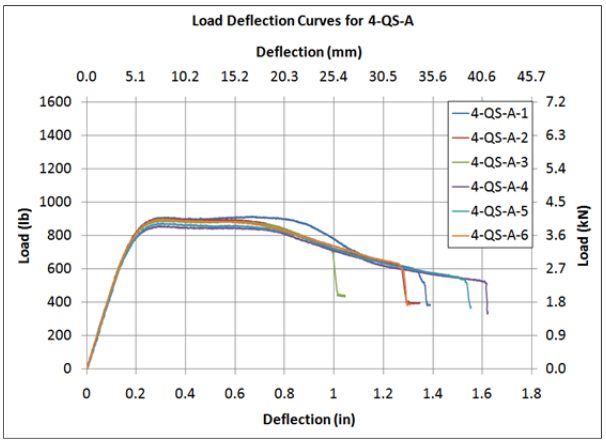
a)



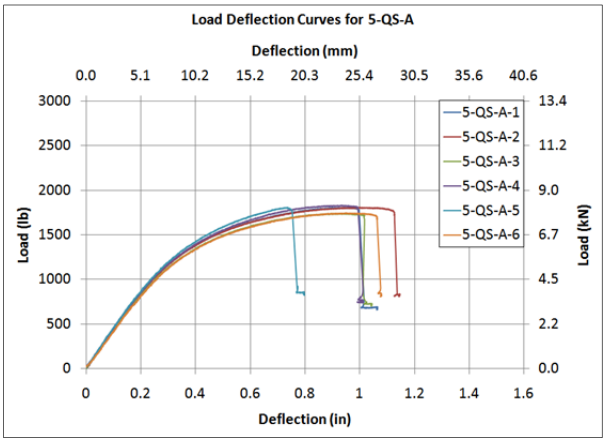
b)



c)

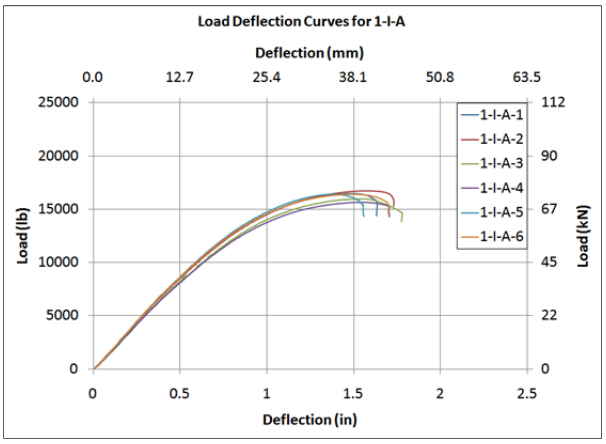


d)

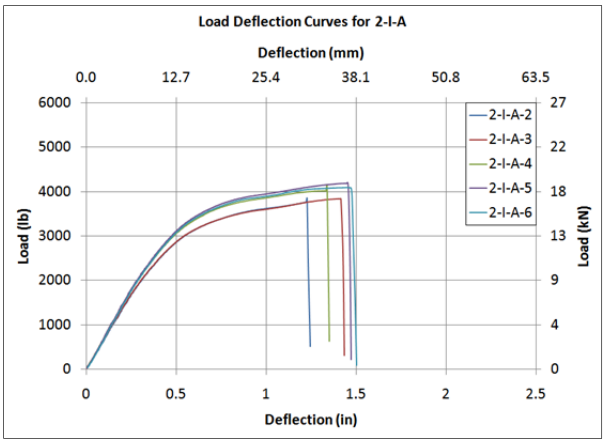


e)

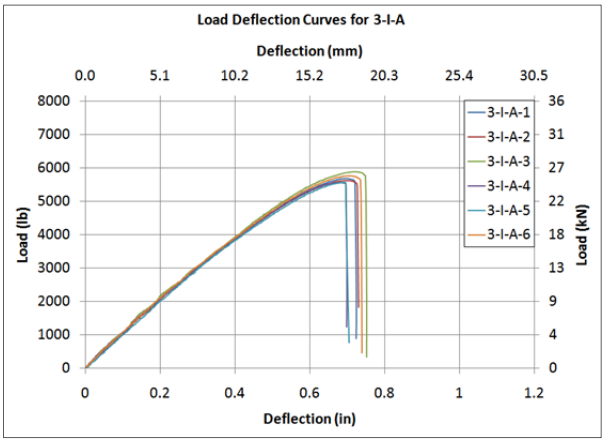
Figure I10: Load deflection curves for the quasi-static speed, standard temperature C393 tests. a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.



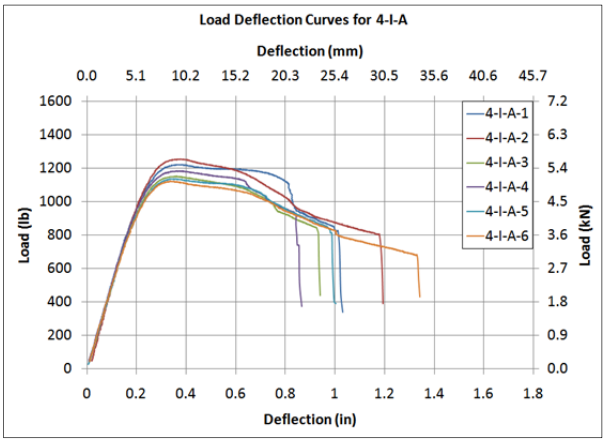
a)



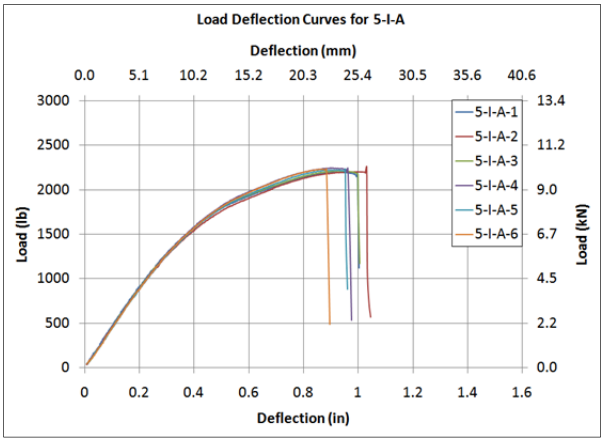
b)



c)

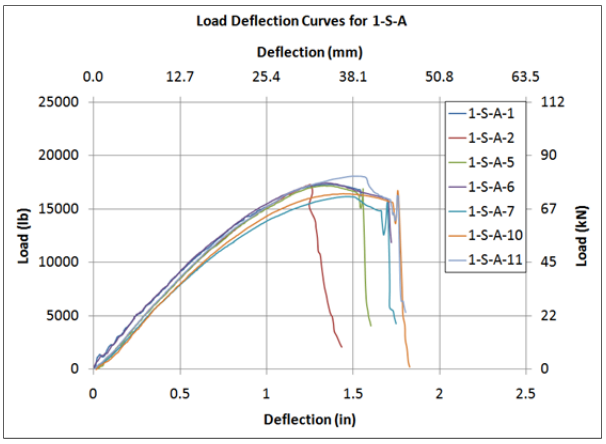


d)

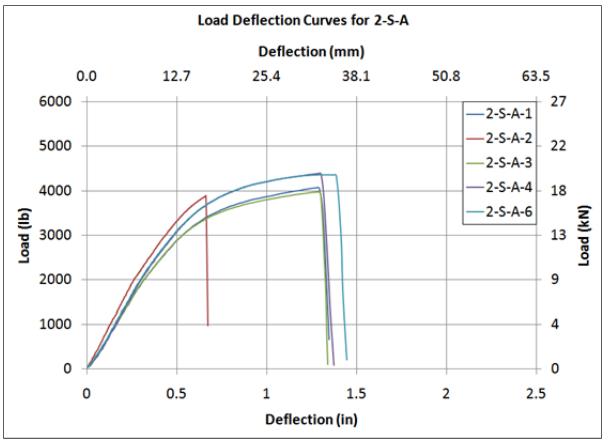


e)

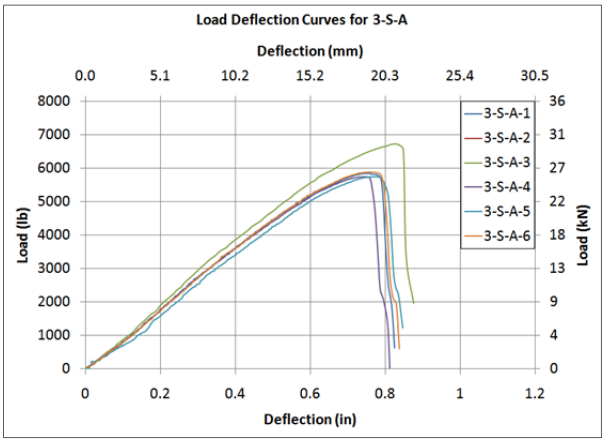
Figure I11: Load deflection curves for the intermediate speed, standard temperature C393 tests. a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.



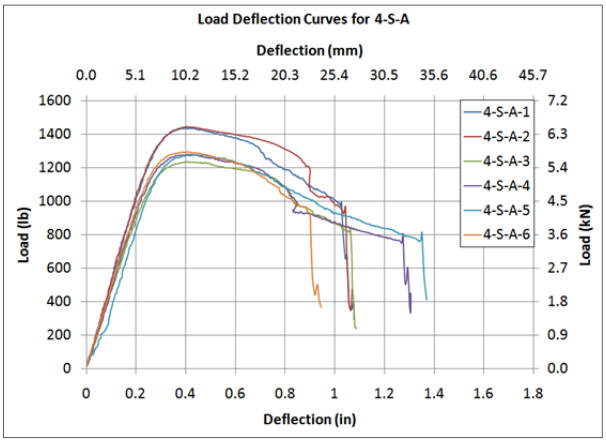
a)



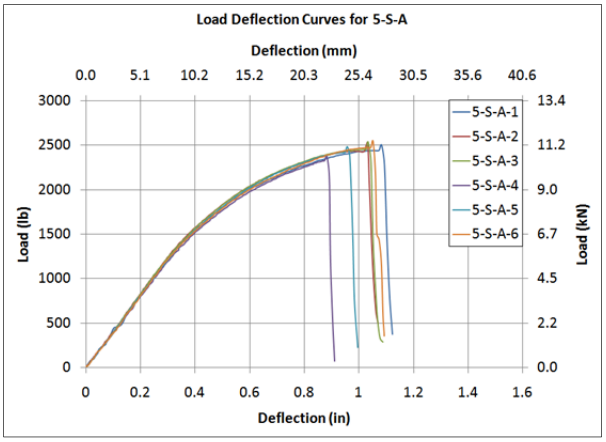
b)



c)



d)



e)

Figure I12: Load deflection curves for the slamming speed, standard temperature C393 tests. a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.

The results of the standard temperature C393 tests:

Table I10a: Standard Temperature (21°C), Quasi-Static Speed (SI units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kN)	*Std Dev (kN)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
1(H130)	6	57.58	3.828	6.65	1.949	0.1208	6.20	52.73	3.792	7.19
2(H100)	6	15.02	0.3913	2.60	1.741	0.04431	2.55	48.03	0.9143	1.90
3(M100)	6	19.65	0.9860	5.02	1.445	0.07466	5.17	65.79	7.236	11.0
4(M80)	6	3.994	0.0965	2.42	0.9437	0.01558	1.65	38.94	1.583	4.07
5(M80)	6	8.030	0.1660	2.07	0.9666	0.02039	2.11	39.61	2.335	5.89

Table I10b: Standard Temperature (70°F), Quasi-Static Speed (English units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kip)	*Std Dev (kip)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
1(H130)	6	12.85	0.8541	6.65	282.6	17.52	6.20	7647	550.0	7.19
2(H100)	6	3.352	0.08730	2.60	252.4	6.427	2.55	6966	132.6	1.90
3(M100)	6	4.383	0.2200	5.02	209.6	10.83	5.17	9543	1049	11.0
4(M80)	6	0.8910	0.02154	2.42	136.9	2.260	1.65	5648	229.6	4.07
5(M80)	6	1.791	0.03703	2.07	140.2	2.957	2.11	5745	338.7	5.89

Table I11a: Standard Temperature (21°C), Intermediate Speed (SI units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kN)	*Std Dev (kN)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
1(H130)	6	73.31	2.126	2.90	2.475	0.06580	2.66	67.91	1.410	2.08
2(H100)	6	18.05	0.7579	4.20	2.095	0.09015	4.30	58.11	2.286	3.93
3(M100)	6	25.46	0.5738	2.25	1.857	0.03666	1.97	84.06	3.890	4.63
4(M80)	6	5.289	0.2314	4.37	1.248	0.05493	4.40	50.20	3.043	6.06
5(M80)	6	10.01	0.0928	0.93	1.208	0.01185	0.98	48.33	3.054	6.32

Table I11b: Standard Temperature (70°F), Intermediate Speed (English units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kip)	*Std Dev (kip)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
1(H130)	6	16.36	0.4743	2.90	358.9	9.543	2.66	9850	204.4	2.08
2(H100)	6	4.027	0.1691	4.20	303.8	13.08	4.30	8429	331.6	3.93
3(M100)	6	5.680	0.1280	2.25	269.3	5.317	1.97	12190	564.2	4.63
4(M80)	6	1.180	0.05162	4.37	180.9	7.967	4.40	7280	441.4	6.06
5(M80)	6	2.233	0.02069	0.93	175.2	1.719	0.98	7010	442.9	6.32

The results of the standard temperature C393 tests (cont.):

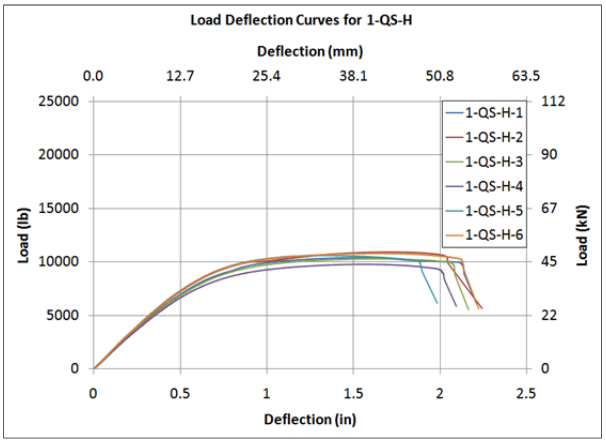
Table I12a: Standard Temperature (21°C), Slamming Speed (SI units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kN)	*Std Dev (kN)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
1(H130)	7	77.97	3.909	5.01	2.677	0.2212	8.26	72.44	5.665	7.82
2(H100)	6	18.54	1.026	5.53	2.154	0.1170	5.43	58.88	3.808	6.47
3(M100)	6	26.01	0.3202	1.23	1.909	0.01073	0.56	85.16	2.860	3.36
4(M80)	6	5.957	0.4038	6.78	1.405	0.08844	6.29	54.91	2.855	5.20
5(M80)	6	11.18	0.2810	2.51	1.354	0.03324	2.45	54.93	2.374	4.32

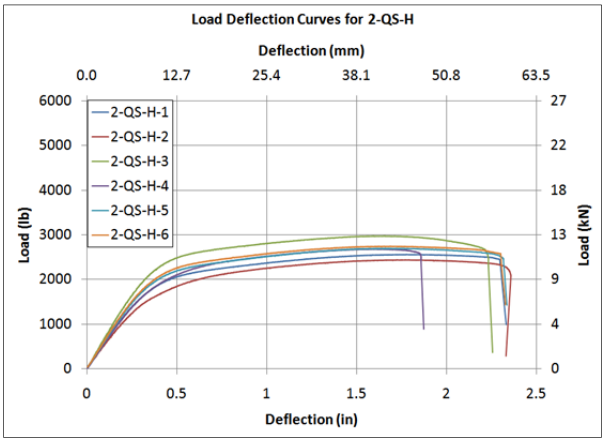
Table I12b: Standard Temperature (70°F), Slamming Speed (English units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kip)	*Std Dev (kip)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
1(H130)	7	17.40	0.8721	5.01	388.2	32.09	8.26	10510	821.7	7.82
2(H100)	6	4.137	0.2289	5.53	312.4	16.96	5.43	8540	552.3	6.47
3(M100)	6	5.802	0.07145	1.23	276.8	1.557	0.56	12350	414.8	3.36
4(M80)	6	1.329	0.09009	6.78	203.8	12.83	6.29	7963	414.1	5.20
5(M80)	6	2.495	0.06268	2.51	196.4	4.821	2.45	7968	344.3	4.32

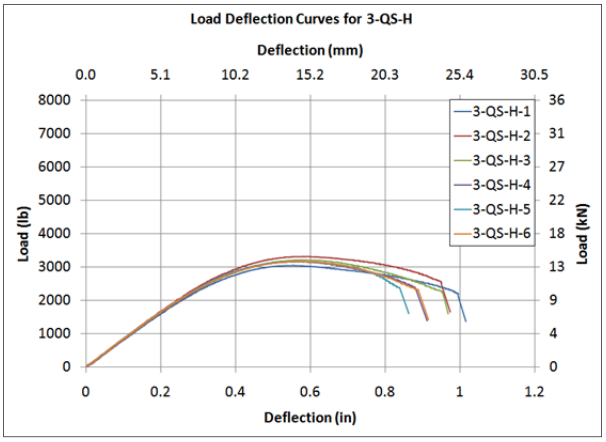
Load-deflection curves for C393 sandwich flexure tests at 60°C (140°F):



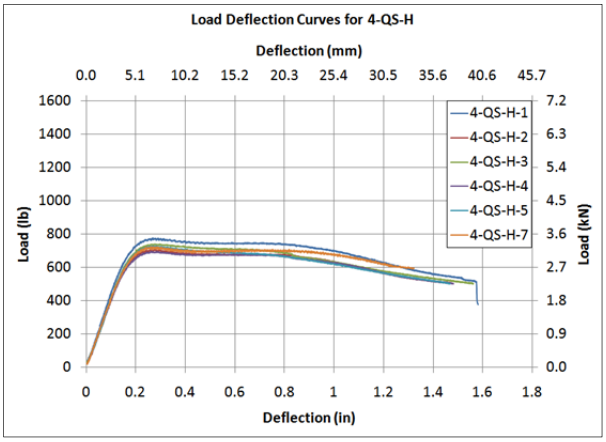
a)



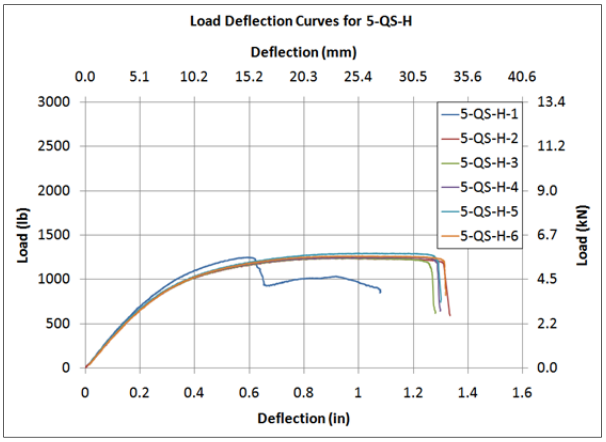
b)



c)

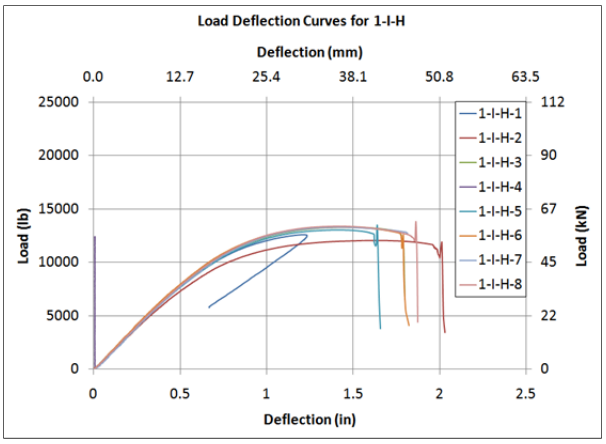


d)

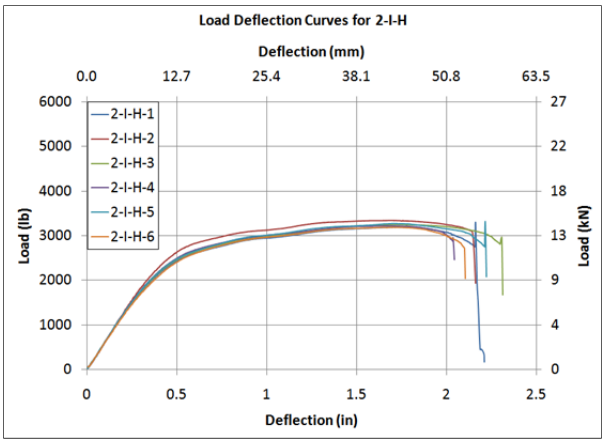


e)

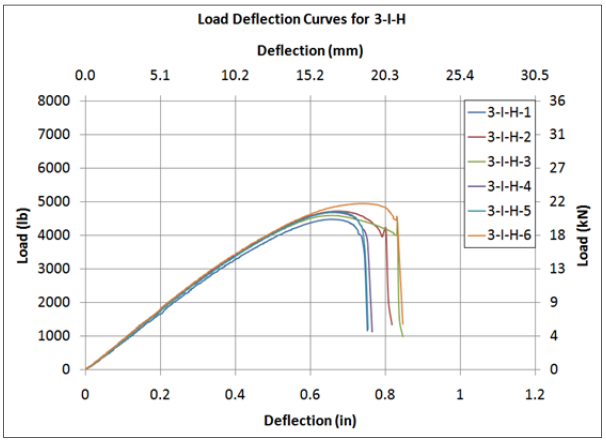
Figure I13: Load deflection curves for the quasi-static speed, high temperature C393 tests. a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.



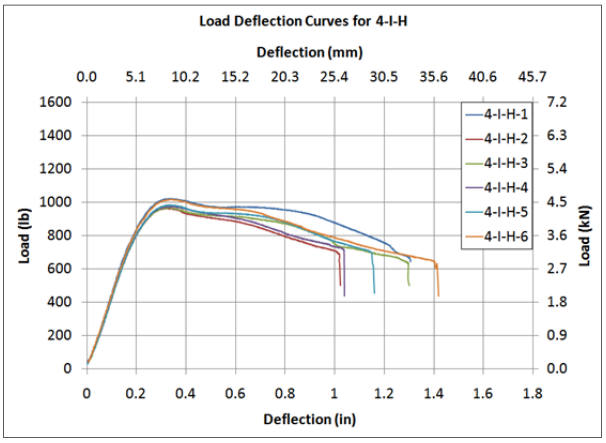
a)



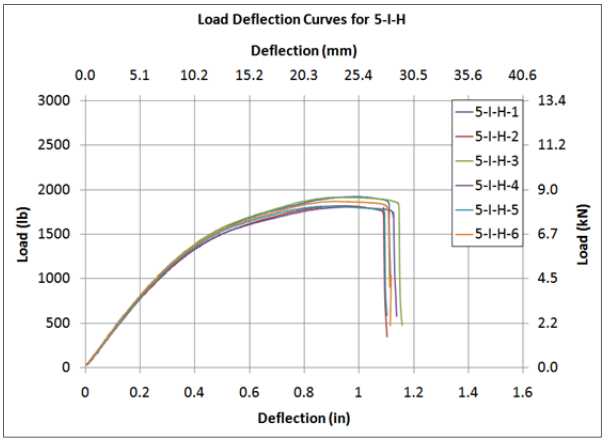
b)



c)

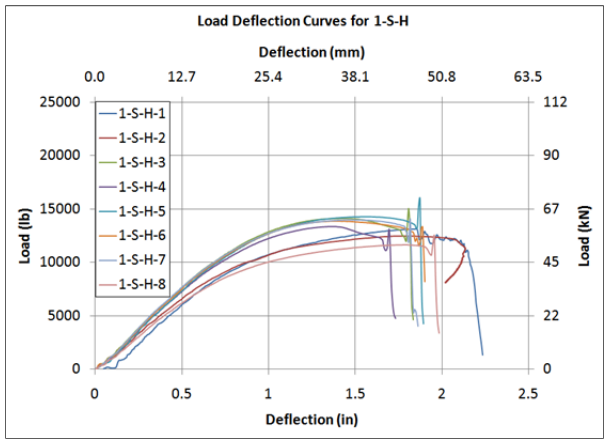


d)

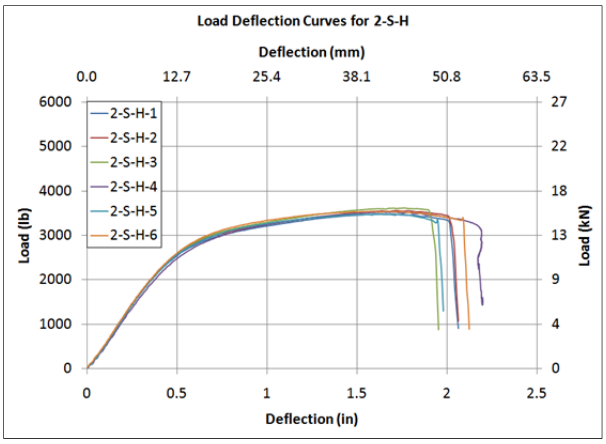


e)

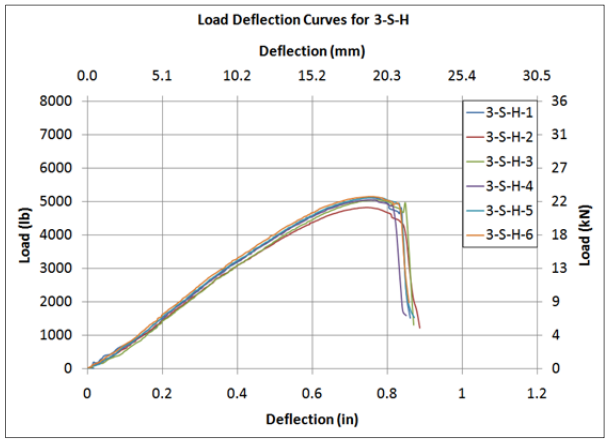
Figure I14: Load deflection curves for the intermediate speed, high temperature C393 tests. a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.



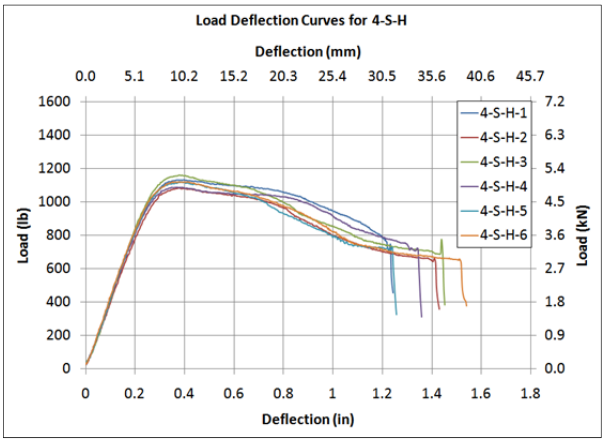
a)



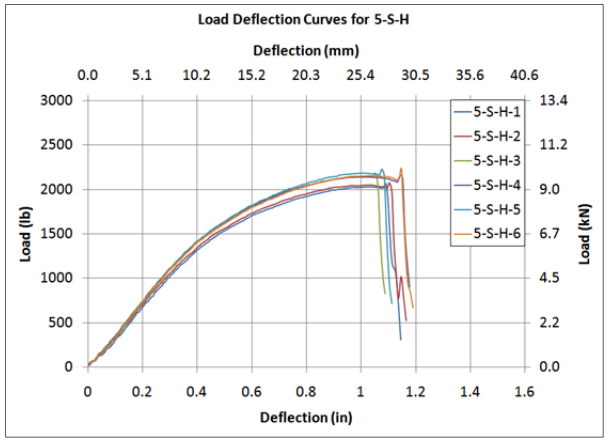
b)



c)



d)



e)

Figure I15: Load deflection curves for the slamming speed, high temperature C393 tests. a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.

The results of the high temperature C393 tests:

Table I13a: High Temperature (60°C), Quasi-Static Speed (SI units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kN)	*Std Dev (kN)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
1(H130)	6	46.96	1.793	3.82	1.584	0.05627	3.55	42.89	1.416	3.30
2(H100)	6	12.04	0.7964	6.61	1.395	0.09211	6.60	38.26	3.006	7.86
3(M100)	6	14.27	0.3691	2.59	1.041	0.02193	2.11	45.46	1.933	4.25
4(M80)	6	3.266	0.1311	4.01	0.7703	0.02762	3.59	31.50	1.609	5.11
5(M80)	6	5.651	0.1068	1.89	0.6824	0.01201	1.76	27.26	0.7483	2.75

Table I13b: High Temperature (140°F), Quasi-Static Speed (English units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kip)	*Std Dev (kip)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
1(H130)	6	10.48	0.4000	3.82	229.7	8.161	3.55	6220	205.4	3.30
2(H100)	6	2.687	0.1777	6.61	202.4	13.36	6.60	5549	436.0	7.86
3(M100)	6	3.184	0.08236	2.59	151.0	3.181	2.11	6594	280.3	4.25
4(M80)	6	0.7288	0.02925	4.01	111.7	4.006	3.59	4569	233.4	5.11
5(M80)	6	1.261	0.02382	1.89	98.97	1.741	1.76	3953	108.5	2.75

Table I14a: High Temperature (60°C), Intermediate Speed (SI units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kN)	*Std Dev (kN)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
1(H130)	8	58.47	2.538	4.34	1.975	0.08013	4.06	54.20	2.083	3.84
2(H100)	6	14.64	0.2601	1.78	1.697	0.02579	1.52	46.86	0.7151	1.53
3(M100)	6	21.01	0.6899	3.28	1.543	0.05221	3.38	68.52	2.194	3.20
4(M80)	6	4.439	0.1060	2.39	1.052	0.02950	2.80	41.57	2.129	5.12
5(M80)	6	8.336	0.2353	2.82	1.006	0.02875	2.86	40.63	1.850	4.55

Table I14b: High Temperature (140°F), Intermediate Speed (English units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kip)	*Std Dev (kip)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
1(H130)	8	13.04	0.5663	4.34	286.4	11.62	4.06	7862	302.1	3.84
2(H100)	6	3.266	0.05802	1.78	246.1	3.740	1.52	6796	103.7	1.53
3(M100)	6	4.689	0.1539	3.28	223.8	7.573	3.38	9937	318.2	3.20
4(M80)	6	0.9903	0.02364	2.39	152.6	4.279	2.80	6030	308.8	5.12
5(M80)	6	1.860	0.05250	2.82	145.9	4.169	2.86	5893	268.3	4.55

The results of the high temperature C393 tests (cont.):

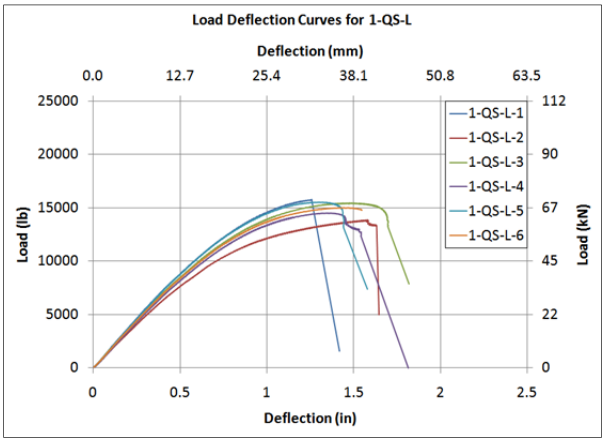
Table I15a: High Temperature (60°C), Slamming Speed (SI units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kN)	*Std Dev (kN)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
1(H130)	8	61.93	5.384	8.69	2.109	0.1668	7.91	57.18	5.125	8.96
2(H100)	6	15.85	0.2446	1.54	1.845	0.03475	1.88	50.83	1.337	2.63
3(M100)	6	22.66	0.5554	2.45	1.659	0.04133	2.49	74.28	3.898	5.25
4(M80)	6	5.008	0.1264	2.52	1.182	0.03663	3.10	46.22	1.950	4.22
5(M80)	6	9.673	0.3251	3.36	1.164	0.03218	2.76	47.81	1.467	3.07

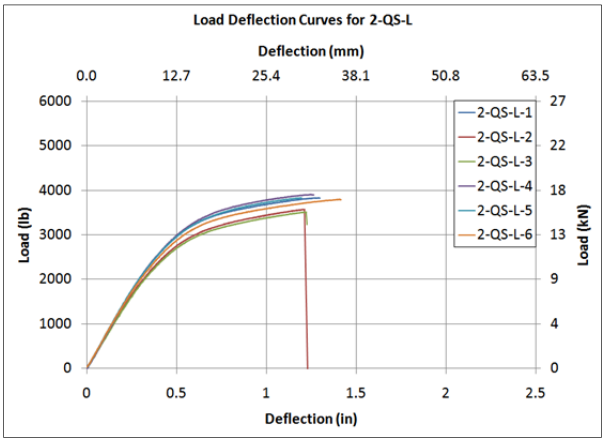
Table I15b: High Temperature (140°F), Slamming Speed (English units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kip)	*Std Dev (kip)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
1(H130)	8	13.82	1.201	8.69	305.8	24.19	7.91	8293	743.3	8.96
2(H100)	6	3.535	0.05457	1.54	267.5	5.040	1.88	7373	194.0	2.63
3(M100)	6	5.057	0.1239	2.45	240.6	5.995	2.49	10770	565.4	5.25
4(M80)	6	1.117	0.02820	2.52	171.4	5.312	3.10	6703	282.9	4.22
5(M80)	6	2.158	0.07253	3.36	168.8	4.667	2.76	6935	212.8	3.07

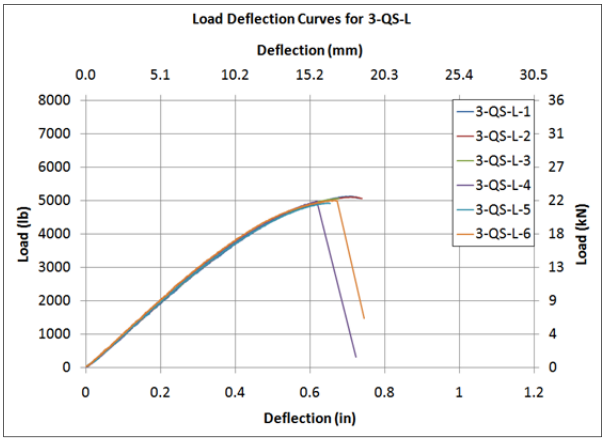
Load-deflection curves for C393 sandwich flexure tests at -12°C (10°F):



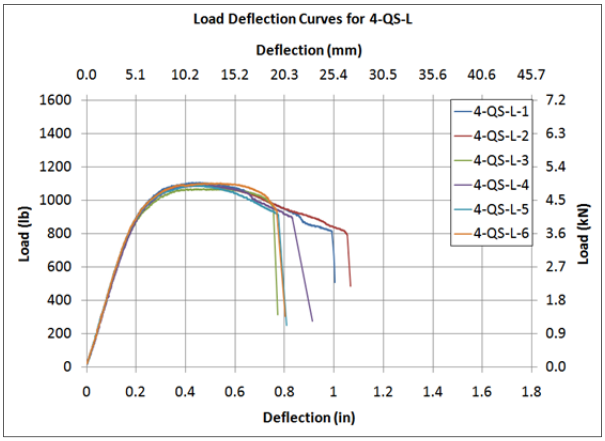
a)



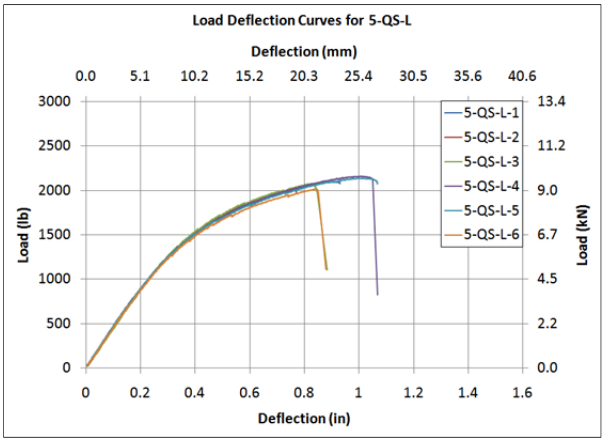
b)



c)

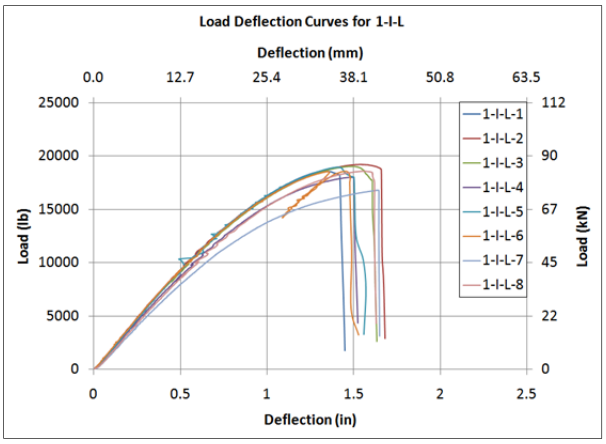


d)

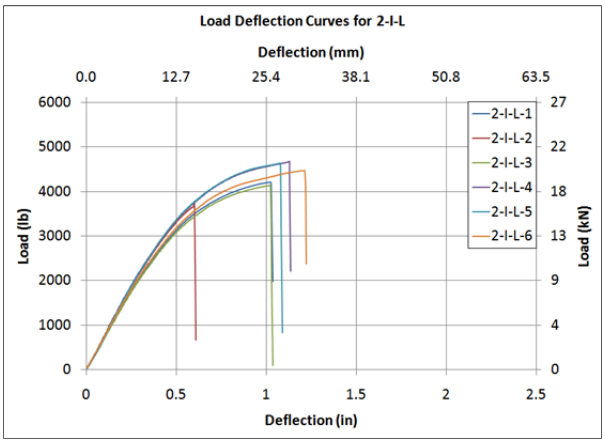


e)

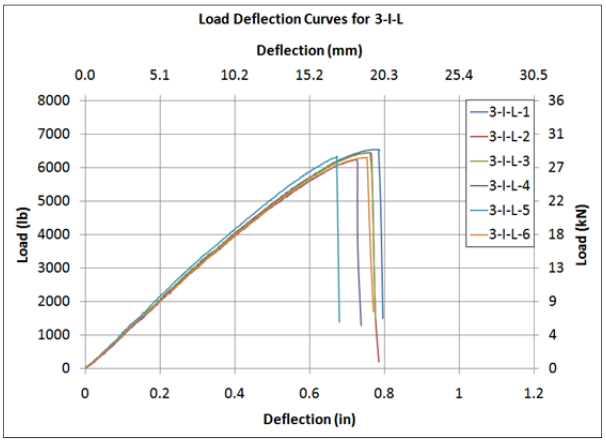
Figure I16: Load deflection curves for the quasi-static, low temperature C393 tests. a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.



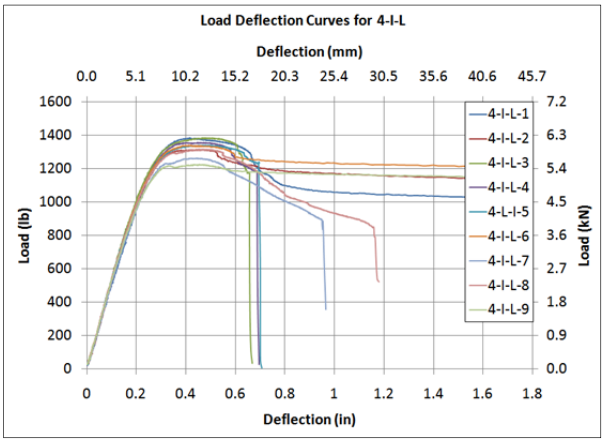
a)



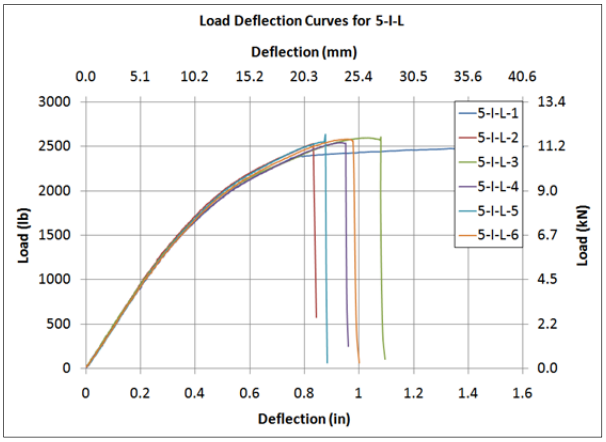
b)



c)

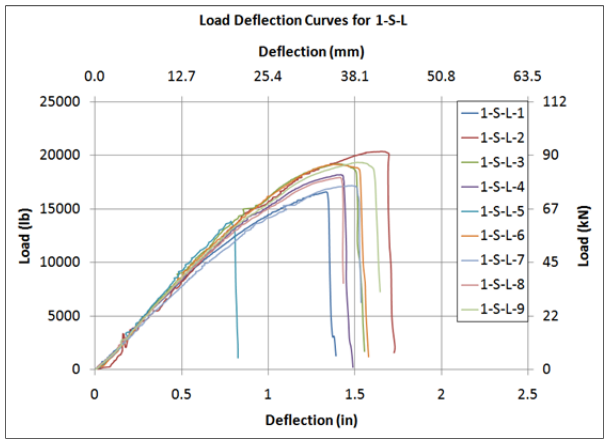


d)

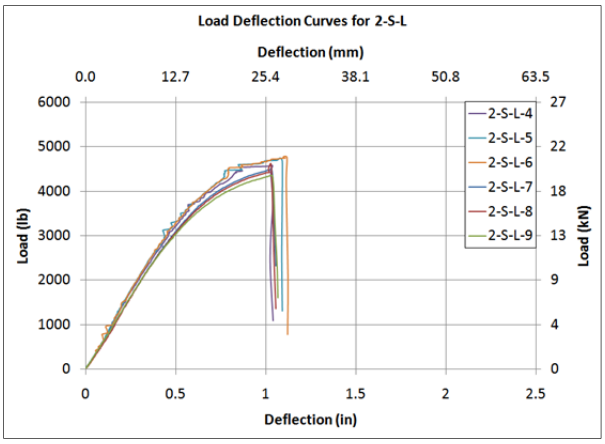


e)

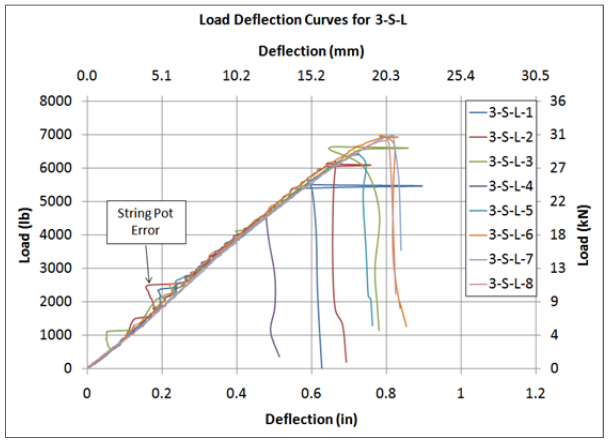
Figure I17: Load deflection curves for the intermediate, low temperature C393 tests. a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.



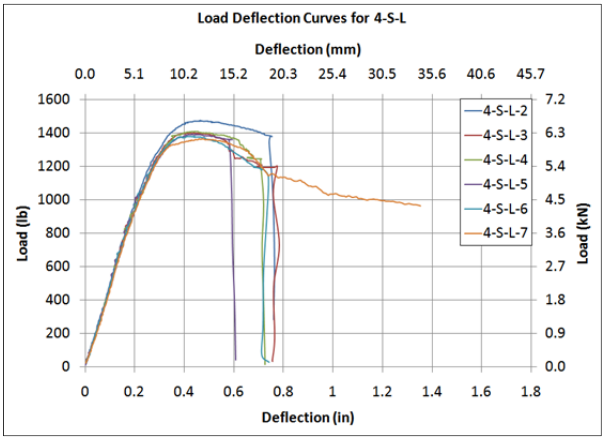
a)



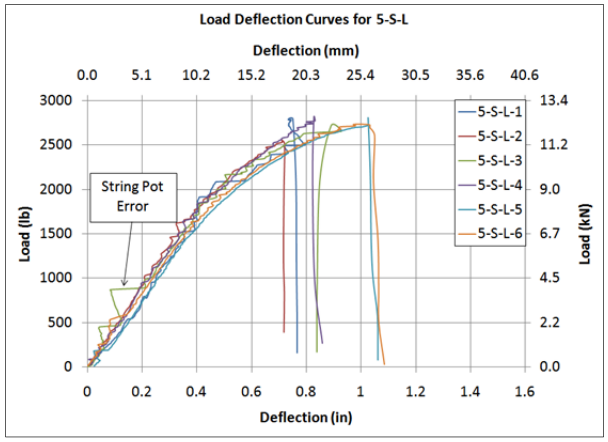
b)



c)



d)



e)

Figure I18: Load deflection curves for the slamming, low temperature C393 tests. a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.

The results of the low temperature C393 tests:

Table I16a: Low Temperature (-12°C), Quasi-Static Speed (SI units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kN)	*Std Dev (kN)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
1(H130)	6	67.42	3.264	4.84	2.272	0.1032	4.54	60.90	2.946	4.84
2(H100)	6	16.79	0.7145	4.26	1.947	0.08060	4.14	53.78	2.944	5.47
3(M100)	6	22.60	0.3543	1.57	1.657	0.02381	1.44	74.40	3.040	4.09
4(M80)	6	4.903	0.0567	1.16	1.159	0.01308	1.13	46.84	1.034	2.21
5(M80)	6	9.339	0.2806	3.00	1.125	0.02738	2.43	46.59	1.123	2.41

Table I16b: Low Temperature (10°F), Quasi-Static Speed (English units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kip)	*Std Dev (kip)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
1(H130)	6	15.04	0.7282	4.84	329.5	14.96	4.54	8834	427.3	4.84
2(H100)	6	3.745	0.1594	4.26	282.4	11.69	4.14	7800	427.1	5.47
3(M100)	6	5.041	0.07904	1.57	240.4	3.453	1.44	10790	440.9	4.09
4(M80)	6	1.094	0.01265	1.16	168.0	1.897	1.13	6794	149.9	2.21
5(M80)	6	2.084	0.06261	3.00	163.2	3.970	2.43	6757	162.9	2.41

Table I17a: Low Temperature (-12°C), Intermediate Speed (SI units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kN)	*Std Dev (kN)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
1(H130)	8	82.77	3.445	4.16	2.879	0.09583	3.33	78.44	3.662	4.67
2(H100)	5	19.85	1.098	5.53	2.306	0.1264	5.48	63.21	3.461	5.48
3(M100)	6	28.61	0.5270	1.84	2.093	0.03659	1.75	93.84	3.805	4.05
4(M80)	9	5.940	0.2387	4.02	1.406	0.05480	3.90	56.44	3.769	6.68
5(M80)	6	11.56	0.1594	1.38	1.391	0.02164	1.56	57.11	1.632	2.86

Table I17b: Low Temperature (10°F), Intermediate Speed (English units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kip)	*Std Dev (kip)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
1(H130)	8	18.47	0.7686	4.16	417.6	13.90	3.33	11380	531.2	4.67
2(H100)	5	4.429	0.2449	5.53	334.4	18.33	5.48	9167	502.0	5.48
3(M100)	6	6.383	0.1176	1.84	303.6	5.307	1.75	13610	551.9	4.05
4(M80)	9	1.325	0.05324	4.02	204.0	7.948	3.90	8186	546.7	6.68
5(M80)	6	2.580	0.03555	1.38	201.8	3.138	1.56	8283	236.6	2.86

The results of the low temperature C393 tests (cont.):

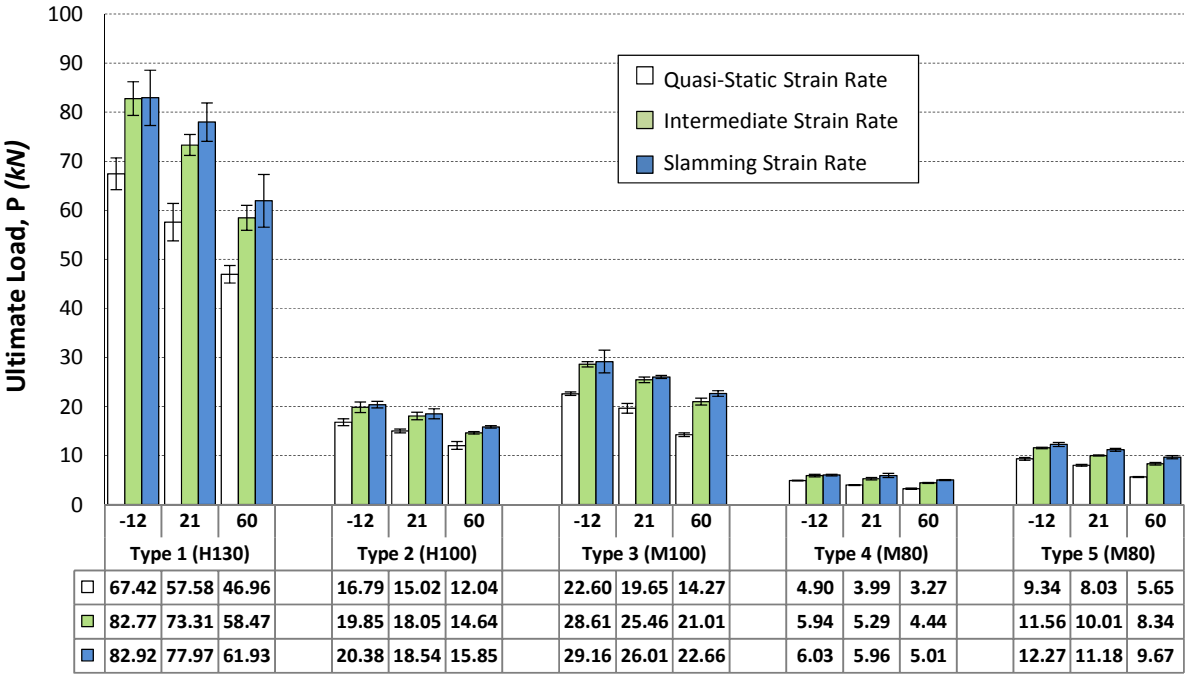
Table I18a: Low Temperature (-12°C), Slamming Speed (SI units)

Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kN)	*Std Dev (kN)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*	*Mean (MPa)*	*Std Dev (MPa)*	*COV (%)*
1(H130)	8	82.92	5.630	6.79	2.833	0.2046	7.22	77.59	5.647	7.28
2(H100)	9	20.38	0.6799	3.34	2.369	0.07640	3.22	65.12	2.737	4.20
3(M100)	7	29.16	2.312	7.93	2.115	0.1507	7.13	96.22	6.086	6.33
4(M80)	7	6.026	0.1708	2.71	1.482	0.04501	3.04	58.09	2.857	4.92
5(M80)	6	12.27	0.4291	3.50	1.472	0.04993	3.39	59.37	2.082	3.51

Table I18b: Low Temperature (10°F), Slamming Speed (English units)

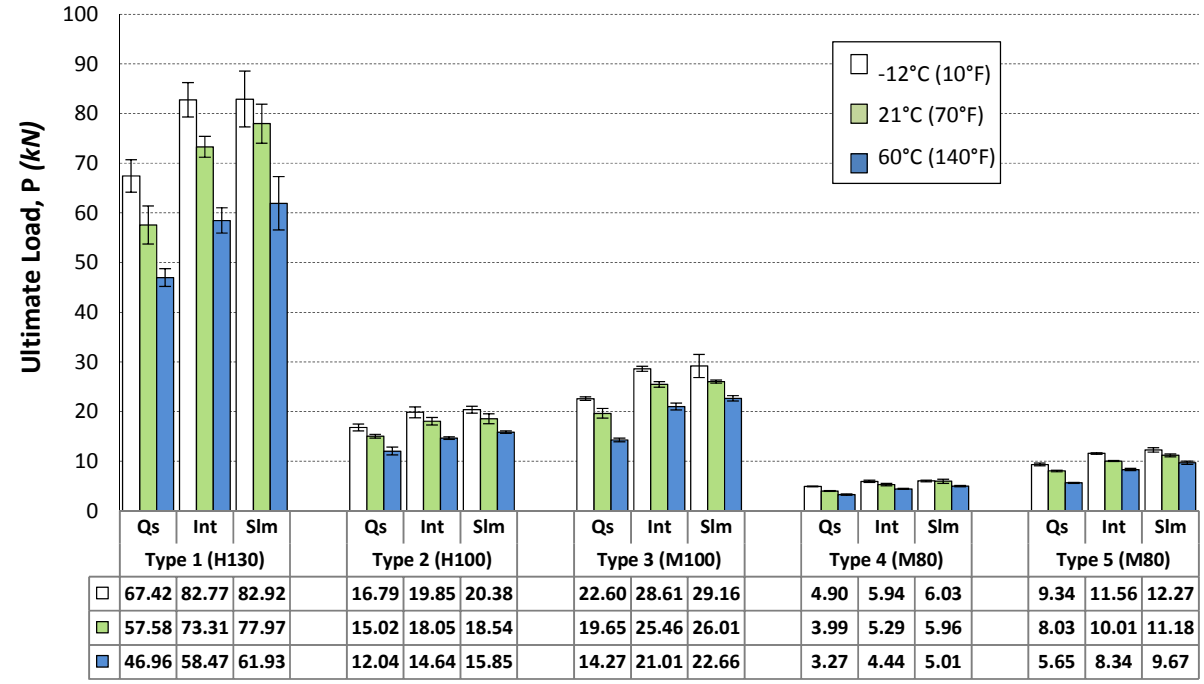
Panel Type	# of Tests	P			τ_{fail}			σ_{face}		
		Mean (kip)	*Std Dev (kip)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*	*Mean (psi)*	*Std Dev (psi)*	*COV (%)*
1(H130)	8	18.50	1.256	6.79	410.9	29.67	7.22	11250	819.0	7.28
2(H100)	9	4.546	0.1517	3.34	343.6	11.08	3.22	9445	396.9	4.20
3(M100)	7	6.505	0.5158	7.93	306.8	21.86	7.13	13960	882.7	6.33
4(M80)	7	1.405	0.03810	2.71	215.0	6.528	3.04	8426	414.4	4.92
5(M80)	6	2.738	0.09574	3.50	213.4	7.241	3.39	8610	301.9	3.51

Plots of the C393 sandwich flexure test results:



	Type 1 (H130)			Type 2 (H100)			Type 3 (M100)			Type 4 (M80)			Type 5 (M80)		
	-12	21	60	-12	21	60	-12	21	60	-12	21	60	-12	21	60
Quasi-Static Strain Rate	67.42	57.58	46.96	16.79	15.02	12.04	22.60	19.65	14.27	4.90	3.99	3.27	9.34	8.03	5.65
Intermediate Strain Rate	82.77	73.31	58.47	19.85	18.05	14.64	28.61	25.46	21.01	5.94	5.29	4.44	11.56	10.01	8.34
Slamming Strain Rate	82.92	77.97	61.93	20.38	18.54	15.85	29.16	26.01	22.66	6.03	5.96	5.01	12.27	11.18	9.67

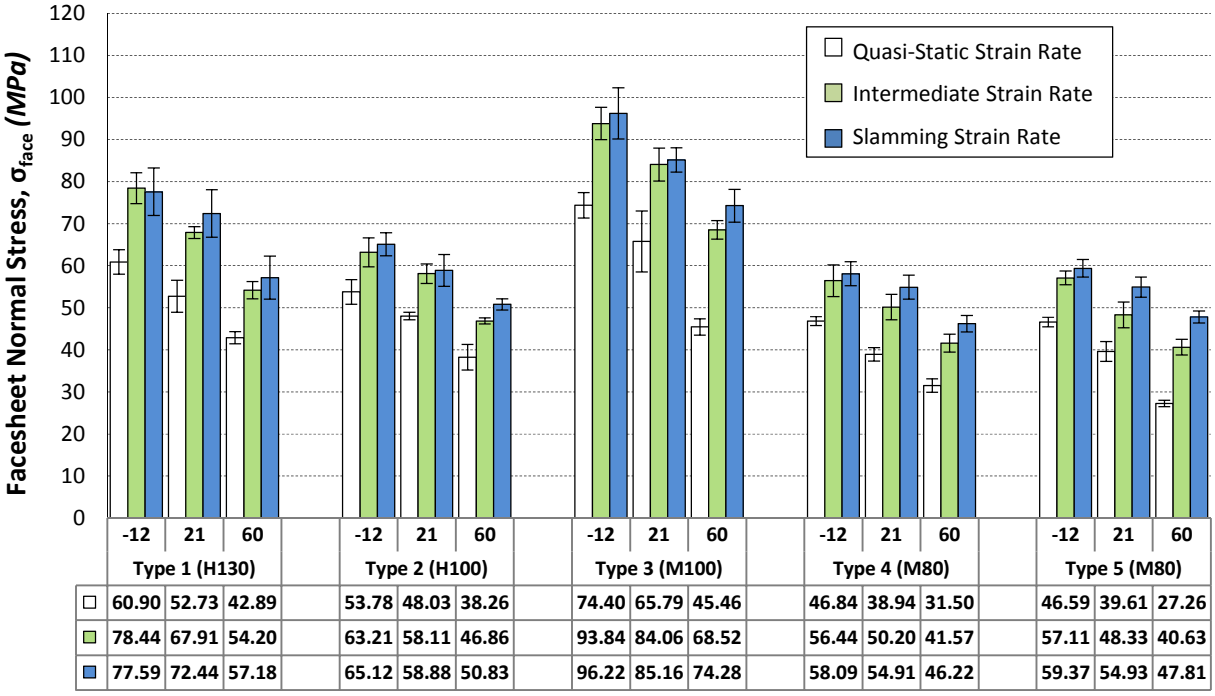
a)



	Type 1 (H130)			Type 2 (H100)			Type 3 (M100)			Type 4 (M80)			Type 5 (M80)		
	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm
-12°C (10°F)	67.42	82.77	82.92	16.79	19.85	20.38	22.60	28.61	29.16	4.90	5.94	6.03	9.34	11.56	12.27
21°C (70°F)	57.58	73.31	77.97	15.02	18.05	18.54	19.65	25.46	26.01	3.99	5.29	5.96	8.03	10.01	11.18
60°C (140°F)	46.96	58.47	61.93	12.04	14.64	15.85	14.27	21.01	22.66	3.27	4.44	5.01	5.65	8.34	9.67

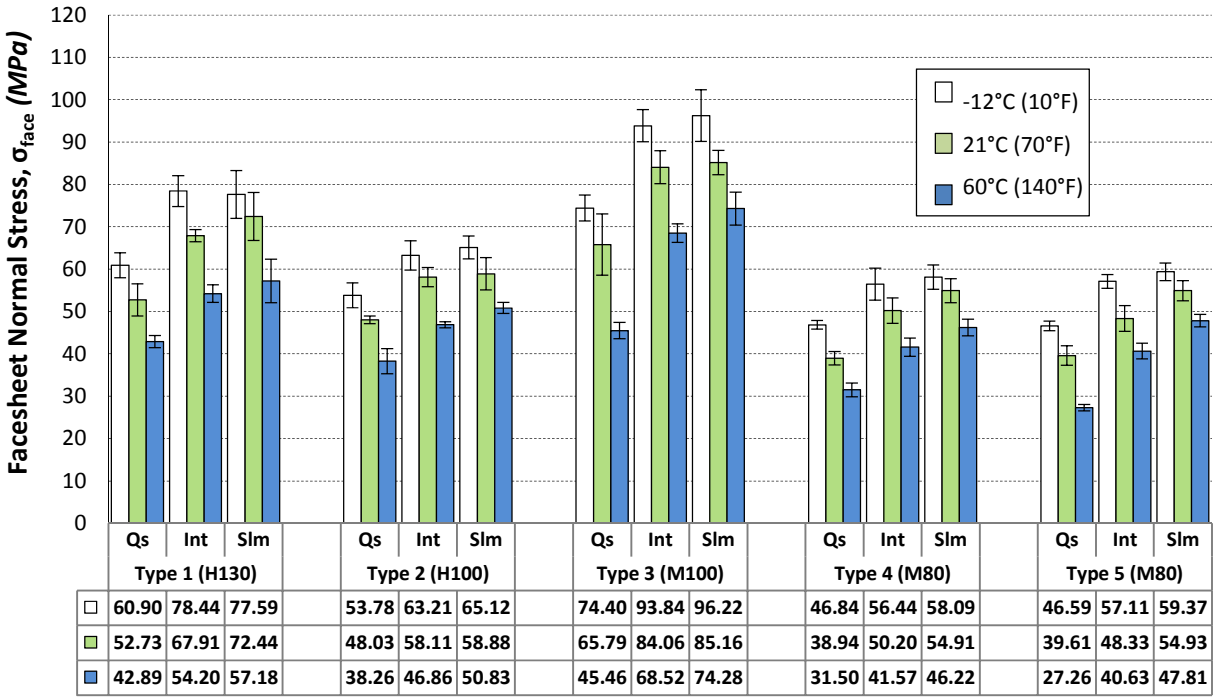
b)

Ultimate load (*P*) results at all temperatures and strain rates grouped by panel type: a) Temperature subsets, b) Strain rate subsets.



	-12	21	60	-12	21	60	-12	21	60	-12	21	60	-12	21	60
	Type 1 (H130)			Type 2 (H100)			Type 3 (M100)			Type 4 (M80)			Type 5 (M80)		
□	60.90	52.73	42.89	53.78	48.03	38.26	74.40	65.79	45.46	46.84	38.94	31.50	46.59	39.61	27.26
	78.44	67.91	54.20	63.21	58.11	46.86	93.84	84.06	68.52	56.44	50.20	41.57	57.11	48.33	40.63
	77.59	72.44	57.18	65.12	58.88	50.83	96.22	85.16	74.28	58.09	54.91	46.22	59.37	54.93	47.81

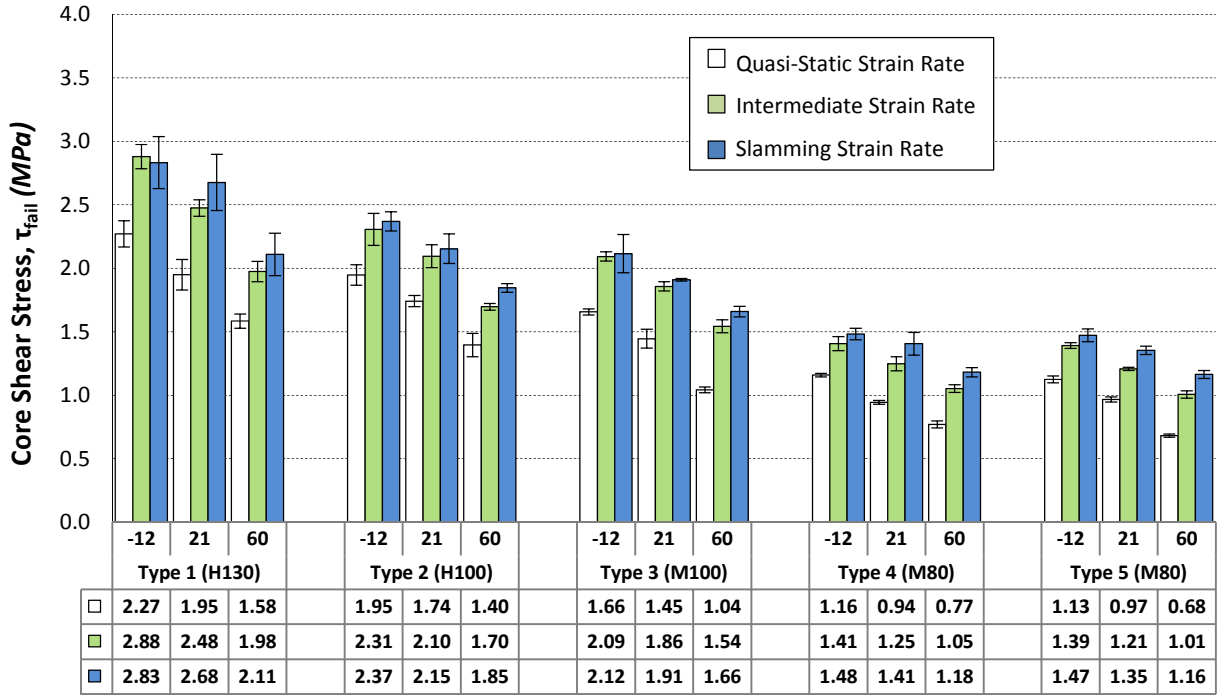
a)



	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm
	Type 1 (H130)			Type 2 (H100)			Type 3 (M100)			Type 4 (M80)			Type 5 (M80)		
□	60.90	78.44	77.59	53.78	63.21	65.12	74.40	93.84	96.22	46.84	56.44	58.09	46.59	57.11	59.37
	52.73	67.91	72.44	48.03	58.11	58.88	65.79	84.06	85.16	38.94	50.20	54.91	39.61	48.33	54.93
	42.89	54.20	57.18	38.26	46.86	50.83	45.46	68.52	74.28	31.50	41.57	46.22	27.26	40.63	47.81

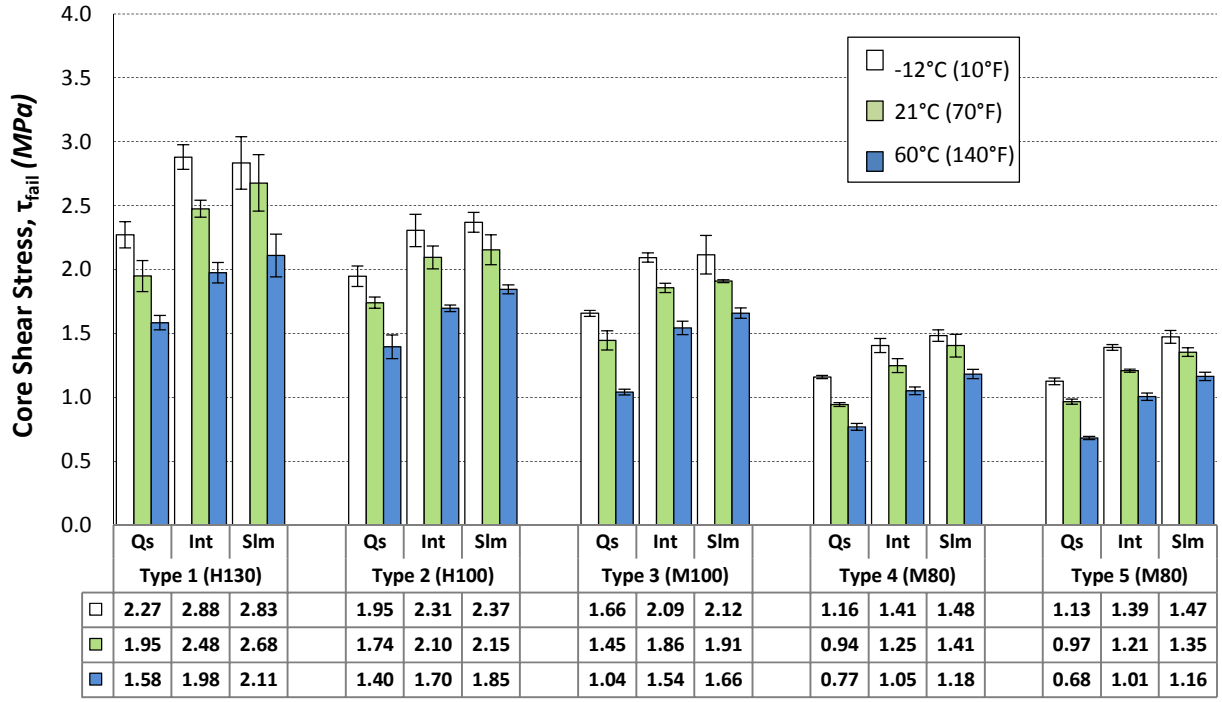
b)

Facesheet normal stress (σ_{face}) results at all temperatures and strain rates grouped by panel type: a) Temperature subsets, b) Strain rate subsets.



	Type 1 (H130)			Type 2 (H100)			Type 3 (M100)			Type 4 (M80)			Type 5 (M80)		
	-12	21	60	-12	21	60	-12	21	60	-12	21	60	-12	21	60
□	2.27	1.95	1.58	1.95	1.74	1.40	1.66	1.45	1.04	1.16	0.94	0.77	1.13	0.97	0.68
■	2.88	2.48	1.98	2.31	2.10	1.70	2.09	1.86	1.54	1.41	1.25	1.05	1.39	1.21	1.01
■	2.83	2.68	2.11	2.37	2.15	1.85	2.12	1.91	1.66	1.48	1.41	1.18	1.47	1.35	1.16

a)



	Type 1 (H130)			Type 2 (H100)			Type 3 (M100)			Type 4 (M80)			Type 5 (M80)		
	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm	Qs	Int	Slm
□	2.27	2.88	2.83	1.95	2.31	2.37	1.66	2.09	2.12	1.16	1.41	1.48	1.13	1.39	1.47
■	1.95	2.48	2.68	1.74	2.10	2.15	1.45	1.86	1.91	0.94	1.25	1.41	0.97	1.21	1.35
■	1.58	1.98	2.11	1.40	1.70	1.85	1.04	1.54	1.66	0.77	1.05	1.18	0.68	1.01	1.16

b)

Core shear stress (τ_{fail}) results at all temperatures and strain rates grouped by panel type: a) Temperature subsets, b) Strain rate subsets.

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Appendix J
Core Mechanics Model

J1. Derivations of the equations for the moment curvature model

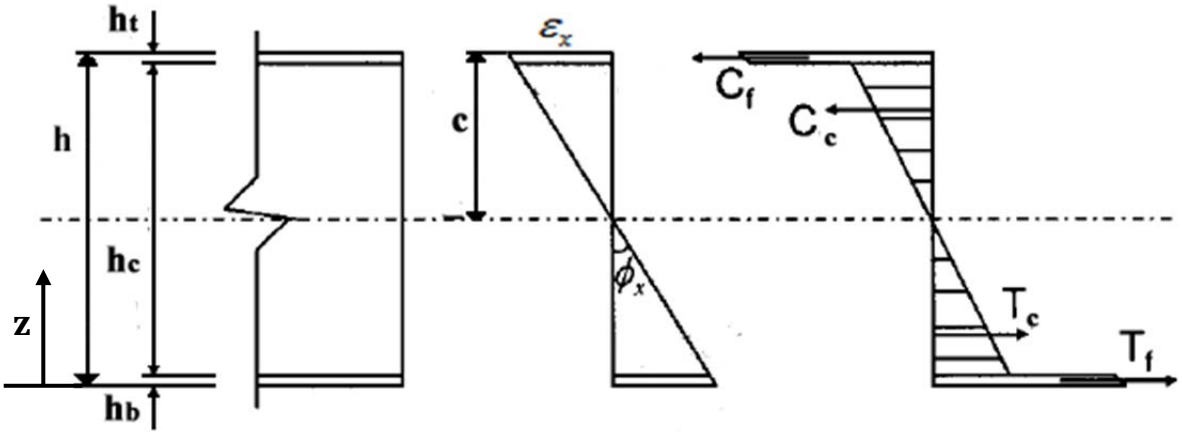


Figure J1. Schematic of the Sandwich Laminate[1]

Equation J1 below is based on equilibrium and must be satisfied:

$$C_f + T_f + C_c + T_c = 0 \tag{J1}$$

Equation J2 below describes the strain in the cross section as a function of *z*.

$$\varepsilon(z) = \frac{\varepsilon_x}{c}(z - h + c) \tag{J2}$$

Equations J3–J6 are the derivations of the components of the equilibrium equation. Equation J2 is substituted into these equations based on first principles.

$$\begin{aligned} C_f &= \sigma_x h_t b \\ C_f &= E_t \varepsilon \left(h - \tfrac{1}{2} h_t\right) h_t b \\ C_f &= E_t \frac{\varepsilon_x}{c}\left(c - \tfrac{1}{2} h_t\right) h_t b \end{aligned} \tag{J3}$$

$$\begin{aligned} T_f &= \sigma_x h_b b \\ T_f &= E_b \varepsilon \left(\tfrac{1}{2} h_b\right) h_b b \\ T_f &= E_b \frac{\varepsilon_x}{c}\left(\tfrac{1}{2} h_b - h + c\right) h_b b \end{aligned} \tag{J4}$$

[1] Lopez-Anido, R. A., & Xu, H. (2002, August). Structural Characterization of Hybrid Fiber-Reinforced Polymer-Glulam Panels for Bridge Decks. Journal of Composites for Construction, 194-203.

$$
\begin{aligned}
C_c &= b\int_{h-c}^{h-h_t}\sigma dz \\
C_c &= bE_c\int_{h-c}^{h-h_t}\varepsilon(z)\,dz \\
C_c &= bE_c\left(\frac{\varepsilon_x}{c}\left(\frac{z^2}{2}-hz+cz\right)\right)\Bigg|_{h-c}^{h-h_t} \\
C_c &= bE_c\left(\frac{\varepsilon_x}{2c}(h_t-c)^2\right)
\end{aligned}
\qquad \textbf{(J5)}
$$

$$
\begin{aligned}
T_c &= b\int_{h_b}^{h-c}\sigma dz \\
T_c &= bE_c\int_{h_b}^{h-c}\varepsilon(z)\,dz \\
T_c &= bE_c\left(\frac{\varepsilon_x}{c}\left(\frac{z^2}{2}-hz+cz\right)\right)\Bigg|_{h_b}^{h-c} \\
T_c &= bE_c\left(\frac{\varepsilon_x}{c}\left(\frac{-c^2}{2}+ch-\frac{h_b^2}{2}+hh_b-ch_b\right)\right)
\end{aligned}
\qquad \textbf{(J6)}
$$

Equation J7 below is the basic equation for the calculation of the moment that the cross section is subjected to.

$$M_x = M_f + M_c \qquad \textbf{(J7)}$$

Equations J8 and J9 are the derivations of the components of the moment equation. Equation J2 is substituted into these equations based on first principles.

$$
\begin{aligned}
M_f &= \left(E_1\varepsilon(h)h_1 - E_3\varepsilon(0)h_3\right)\frac{hb}{2} \\
M_f &= \left(E_1\varepsilon_x h_1 - E_3\frac{\varepsilon_x}{c}(c-h)h_3\right)\frac{hb}{2}
\end{aligned}
\qquad \textbf{(J8)}
$$

$$M_c = bE_2 \int_{h_3}^{h-h_1} \varepsilon(z)\, z dz$$

$$M_c = bE_2 \left(\frac{\varepsilon_x}{c} \left(\frac{z^3}{3} - \frac{hz^2}{2} + \frac{cz^2}{2} \right) \right) \Bigg|_{h_3}^{h-h_1} \qquad \textbf{(J9)}$$

$$M_c = bE_2 \left(\frac{\varepsilon_x}{c} \left(\frac{-h^3 + 3hh_1^2 - 2h_1^3}{6} + \frac{c(h-h_1)^2}{2} - h_3^2 \left(\frac{h_3}{3} + \frac{h}{2} - \frac{c}{2} \right) \right) \right)$$

J2. The Matlab code for the five modules:

The following seven Matlab functions make up the three point bend code. The ***Model_3_point_bend*** function is the driver function and it calls the functions for the five modules:

- The ***Moment_Curvature_Analysis*** function is the first module and it calls the ***Neutral_Axis*** function.
- The ***Load_and_Shear_3_point_bend*** function is the second module.
- The ***Shear_Stress_Strain_Modulus*** function is the third module.
- The ***Deflection_3_point_bend*** function is the fourth module.
- The ***Failure_Criteria*** function is the fifth module.

Any function tagged with *3_point_bend* is exclusive for a three point bend test and would need to be modified for different loading or boundary conditions.

J2.1 "Model_3_point_bend" Function

```
function [P,delta] = Model_3_point_bend(b,t,E,L,parameters,limits)
% [P,delta] = Model_3_point_bend(ex,b,t,E,L,parameters,limits)
% This function calculates the load and position for a three point bend
% when supplied with the beam geometry.  It is set up to calculate multiple
% scenarios, where each scenario is represented in a row of the inputs,
% therefore the first row in each vector or matrix input gets used for the
% first scenario.
% Inputs:
%       b = width of section [in]
%       t = vector of thicknesses in the form [t_compression_skin, t_core,
%           t_tension_skin] [in]
%       E = elastic modului of the layers in the form [E_compression_skin,
%           E_core, E_tension_skin] [psi]
%       L = length of section [in]
%       parameters = specific parameters for the curve fit of the core
%           material and density in the form [tau_max, G] [psi]
%       limits = stress/strain limits of the materials and interface in the
%           form [max_strain_compression, max_stress_compression, ... ]
%           [in/in, psi, ...]
%
% Calculated Values:
%       Mx = Moment applied to the section [lb in]
%       e = vector of average strain in compression (top) and tension
%           (bottom) skin in form [e_compression, e_tension] [in/in]
%       P = Load applied to the section [lb]
%       V = Shear force applied to the section [lb]
%       tau = shear stress at shear V [psi]
%       gamma = shear strain at shear V [in/in]
%       G = shear modulus at shear V [psi]
%       del = deflection between this load and the last one [in]
%       loop = binary indicator if the limits have been exceeded.  1 if
%           limits have not been exceeded, 2 if limits have been exceeded
%
% Outputs:
%       P = Vector of loads in the form [...,P_last,P_now] [lb]
%       delta = vector of deflections in the form
%           [...,delta_last,delta_now] [in]
%
```

```
% Calculate the number of runs
n = size(t);
for i = 1:n(1,1)

    % Set up loop
    loop = 1;
    ex(i,2) = 0.0001;
    delta(i,1) = 0;
    count = 2;
    max = 1000;
    while loop == 1 && count<max
        % Do a Moment Curvature Analysis
        [Mx(count),e(count,:)] = Moment_Curvature_Analysis(ex(i,count),...
            b(i,:),t(i,:),E(i,:));

        % Calculate the load and shear force
        [P(i,count),V(count)] = Load_and_Shear_3_point_bend(Mx(count),...
            L(i,:));

        % Calculate the shear stress, shear strain, and shear modulus
        [tau(count),gamma(count),G(count)] = Shear_Stress_Strain_Modulus ...
            (V(count),parameters(i,:),b(i,:),t(i,:),E(i,:));

        % Calculate the increment of deflection and deflection
        [del] = Deflection_3_point_bend(P(i,1:count),b(i,:),L(i,:),t(i,:),...
            E(i,:),G(count));
        delta(i,count)=delta(i,count-1)+del;

        % Check if deflection is real or imaginary and if the increment of
        % deflection is positive
        if isreal(delta(i,count)) == 0
            delta(i,count) = 0;
            P(i,count) = 0;
            break
        elseif del < 0
            delta(i,count) = 0;
            P(i,count) = 0;
            break
        else
        end

        % Check the failure criteria
        [loop] = Failure_Criteria(E,e(count,:),tau(count),gamma(count),...
            limits(i,:));

        % Increase iteration
        count = count + 1;
        ex(i,count) = ex(i,count-1) + 0.0001;
    end

    % Calculate and display the failure ratios
    failure(1) = abs(e(count-1,1))/limits(i,1);
    failure(2) = abs(e(count-1,1)*E(1))/limits(i,2);
    failure(3) = abs(gamma(count-1))/limits(i,3);
    failure(4) = abs(tau(count-1))/limits(i,4);
```

```
    failure(5) = abs(e(count-1,2))/limits(i,5);
    failure(6) = abs(e(count-1,2)*E(3))/limits(i,6);
    if loop == 1
        disp('Model failed due to the shear stress approaching the asymptote
of the hyperbolic tangent function')
        disp(['The strain failure ratio of the compression skin is ',
num2str(failure(1))])
        disp(['The stress failure ratio of the compression skin is ',
num2str(failure(2))])
        disp(['The strain failure ratio of the core is ',
num2str(failure(3))])
        disp(['The stress failure ratio of the core is ',
num2str(failure(4))])
        disp(['The strain failure ratio of the tension skin is ',
num2str(failure(5))])
        disp(['The stress failure ratio of the tension skin is ',
num2str(failure(6))])
        disp(' ')
    else
        disp(['The strain failure ratio of the compression skin is ',
num2str(failure(1))])
        disp(['The stress failure ratio of the compression skin is ',
num2str(failure(2))])
        disp(['The strain failure ratio of the core is ',
num2str(failure(3))])
        disp(['The stress failure ratio of the core is ',
num2str(failure(4))])
        disp(['The strain failure ratio of the tension skin is ',
num2str(failure(5))])
        disp(['The stress failure ratio of the tension skin is ',
num2str(failure(6))])
        disp(' ')
    end
end
```

J2.2 "Moment_Curvature_Analysis" Function *(Module 1)*

```
function [Mx,e] = Moment_Curvature_Analysis(ex,b,t,E)
% [Mx] = Moment_Curvature_Analysis(ex,b,t,E)
% This function calculates the moment applied to a section when it is
% subjected to the strain ex at the top fiber
% Inputs:
%       ex = strain at the top fiber of the section [in/in]
%       b = width of section [in]
%       t = vector of thicknesses in the form [t_compression_skin, t_core,
%           t_tension_skin] [in]
%       E = elastic modului of the layers in the form [E_compression_skin,
%           E_core, E_tension_skin] [psi]
%
% Calculated Values:
%       c = The distance to the neutral axis from the top of the section
%           [in]
% Outputs:
%       Mx = Moment applied to the section [lb in]
%       e = vector of average strain in compression (top) and tension
```

```
%           (bottom) skin in form [e_compression, e_tension] [in/in]

% Use Newton's Method to find c
f = @Neutral_Axis;
c = sum(t)/2;
y_c = f(c,ex,b,t,E);
delc = .01;
tol = 1e-8;
num_iter = 1;
max_iter = 100;

while (abs(y_c) > tol) && (num_iter <= max_iter)
    % Compute the derivative of f
    derf = (f(c+delc,ex,b,t,E)-y_c)/delc;

    num_iter = num_iter + 1;   %increase the iteration

    c = c-(y_c/derf);         %Compute the new c and y_c
    y_c = f(c,ex,b,t,E);
end

% Calculate Mx
Mx = (E(1)*ex*t(1)-E(3)*ex*(c-sum(t))*t(3)/c)*0.5*b*sum(t) +
b*E(2)*((ex/c)*...
    ((1/6)*(-sum(t)^3 + 3*sum(t)*t(1)^2 - 2*t(1)^3) + 0.5*c*(sum(t)-t(1))^2
...
    -t(3)^3*((t(3)/3) + sum(t)/2 - c/2)));

% Calcuate the strains for the top and bottom skins
e = [(ex/c)*(c-0.5*t(1)),(ex/c)*(c+0.5*t(3)-sum(t))];
```

J2.3 "Neutral_Axis" Function *(called by Module 1)*

```
function [f] = Neutral_Axis(c,ex,b,t,E)
% [f] = Neutral_Axis(c,E,ex,t,b)
% This function is used in Newton's Method to find the neutral axis of a
% three layer composite
% Inputs:
%       c = The distance to the neutral axis from the top of the section
%           [in]
%       ex = strain at the top fiber of the section [in/in]
%       b = width of section [in]
%       t = vector of thicknesses in the form [t_compression_skin, t_core,
%           t_tension_skin] [in]
%       E = elastic modului of the layers in the form [E_compression_skin,
%           E_core, E_tension_skin] [psi]
% Outputs:
%       f = 0 when c is correct

f = E(1)*t(1)*b*ex*(c-0.5*t(1))/c + E(3)*t(3)*b*ex*(c+0.5*t(3)-sum(t))/c +
...
    b*E(2)*((ex/(2*c))*(t(1)-c)^2) + b*E(2)*((ex/c)*(-0.5*c^2 + c*sum(t) -
...
    0.5*t(3)^2 + sum(t)*t(3) - c*t(3)));
```

J2.4 "Load_and_Shear_3_point_bend" Function *(Module 2)*

```
function [P,V] = Load_and_Shear_3_point_bend(Mx,L)
% [P,V] = Neutral_Axis (Mx,L)
% This function calculates the load and shear force for a given moment
% under a three point bend
% Inputs:
%       Mx = Applied moment on the section [lb in]
%       L = length of section [in]
%
% Outputs:
%       P = Load applied to the section [lb]
%       V = Shear force applied to the section [lb]

P = (4*Mx)/L;     % Calculate the load applied to the section

V = P/2;          % Calculate the shear force applied to the section
```

J2.5 "Shear_Stress_Strain_Modulus" Function *(Module 3)*

```
function [tau, gamma, G] = Shear_Stress_Strain_Modulus (V,parameters,b,t,E)
% [tau, gamma, G] = Shear_Stress_Strain_Modulus (V, parameters, b, t, E)
% This function calculates the core shear stress, strain and modulus at a
% specific shear force
% Inputs:
%       V = shear force [lb]
%       parameters = specific parameters for the curve fit of the core
%           material and density in the form [tau_max, G] [psi]
%       b = width of section [in]
%       t = vector of thicknesses in the form [t_compression_skin, t_core,
%           t_tension_skin] [in]
%       E = elastic modului of the layers in the form [E_compression_skin,
%           E_core, E_tension_skin] [psi]
%
% Calculated Values:
%       EI = moment of inertia of the section [lb-in^2]
%       EQ = first moment of the area above the point of interest, about
%           the neutral axis [lb-in]
%       strain = shear strain at V minus and plus 0.0001 [in/in]
%       stress = shear stress corresponding to shear strain at V minus and
%           plus 0.0001 [psi]
%
% Outputs:
%       tau = shear stress at shear V [psi]
%       gamma = shear strain at shear V [in/in]
%       G = shear modulus at shear V [psi]

% Calculate EI and EQ
%[EI, EQ] = section_properties(b,t,E);

% Calculate the shear stress
% tau = (V*EQ)/(EI*b);
% tau = V/(b*sum(t));
% tau = V/(b*t(2));
d = t(1)/2 +t(2) +t(3)/2;
```

```
tau = V/(b*d);

% Calculate the shear strain using the curve fit
gamma = (parameters(1)/parameters(2))*atanh(tau/parameters(1));

% Calculate the shear modulus
strain = [gamma-0.0001, gamma+0.0001];
stress = [parameters(1)*tanh(parameters(2)*strain(1)/parameters(1)), ...
    parameters(1)*tanh(parameters(2)*strain(2)/parameters(1))];
G = (stress(2) - stress(1))/(strain(2) - strain (1));
```

J2.6 "Deflection_3_point_bend" Function *(Module 4)*

```
function [del] = Deflection_3_point_bend(P,b,L,t,E,G)
% [delta] = Deflection_3_point_bend(P,b,L,t,E,G)
% This function calculates the three point bend deflection of the beam
% between this ex and the last
% Inputs:
%       P = Vector of loads in the form [...,P_last,P_now] [lb]
%       b = width of section [in]
%       L = length of beam [in]
%       t = vector of thicknesses in the form [t_compression_skin, t_core,
%           t_tension_skin] [in]
%       E = elastic modului of the layers in the form [E_compression_skin,
%           E_core, E_tension_skin] [psi]
%       G = shear modulus of the core [psi]
%
% Calculated Values:
%       D = bending stiffness of the section [lb-in^2]
%       U = shear rigidity of the section [lb]
%       Delta_P = Change in load from the last load to the current load
%           [lb]
% Outputs:
%       del = deflection between this load and the last one [in]

% Calculate D and U to be used in the deflection equation
D = (E(1)*t(1)*E(3)*t(3)*b*(sum(t) + t(2))^2)/(4*(E(1)*t(1) + E(3)*t(3)));
U = (G*b*(sum(t)+t(2))^2)/(4*t(2));

% Calcuate the change in load
num_iter = size(P);
Delta_P = P(num_iter(2))-P(num_iter(2)-1);

% Calculate the deflection between the two loads
del = (Delta_P*L^3)/(48*D) + (Delta_P*L)/(4*U);
```

J2.7 "Failure_Criteria" Function *(Module 5)*

```
function [loop] = Failure_Criteria(E,e,tau,gamma,limits)
% [loop] = Failure_Criteria(e, gamma, limits)
% This function checks to see if the failure criteria have been exceeded
% for the skins, the core, or the interface
```

```
% Inputs:
%       E = elastic modului of the layers in the form [E_compression_skin,
%           E_core, E_tension_skin] [psi]
%       e = vector of average strain in compression (top) and tension
%           (bottom) skin in form [e_compression, e_tension] [in/in]
%       tau = shear stress at shear V [psi]
%       gamma = shear strain at shear V [in/in]
%       limits = stress/strain limits of the materials and interface in the
%           form [max_strain_compression, max_stress_compression, ... ]
%           [in/in, psi, ...]
% Outputs:
%       loop = binary indicator if the limits have been exceeded.  1 if
%           limits have not been exceeded, 2 if limits have been exceeded

% Check top skin in compression
if abs(e(1)) >= limits(1)
    loop(1) = 2;
else
    loop(1) = 1;
end

if abs(e(1)*E(1)) >= limits(2)
    loop(2) = 3;
else
    loop(2) = 1;
end

% Check core in shear
if abs(gamma) >= limits(3)
    loop(3) = 4;
else
    loop(3) = 1;
end

if abs(tau) >= limits(4)
    loop(4) = 5;
else
    loop(4) = 1;
end

% Check bottom skin in tension
if abs(e(2)) >= limits(5)
    loop(5) = 6;
else
    loop(5) = 1;
end

if abs(e(2)*E(3)) >= limits(6)
    loop(6) = 2;
else
    loop(6) = 1;
end

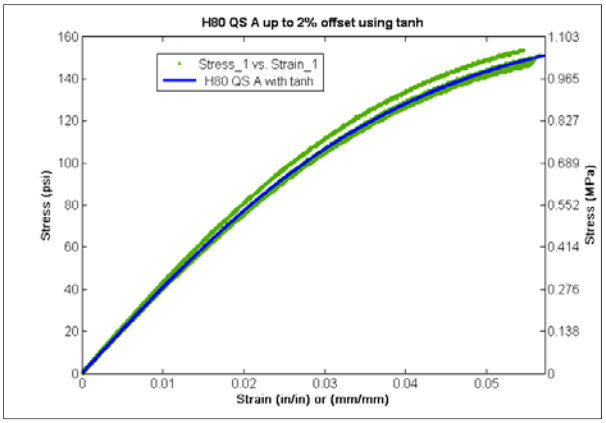
% Check interface
```

```
% Compute max loop
loop = max(loop);
```

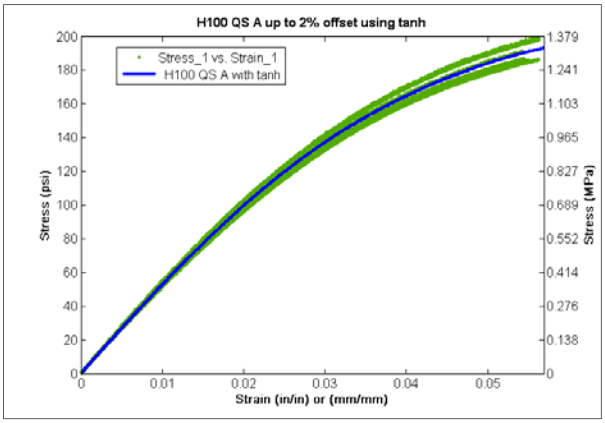
J3. The Plots of the Curve-fits for the C273 Data.

The curve fits are based on the same number of tests listed in Appendix I for each core type, strain rate, and temperature.

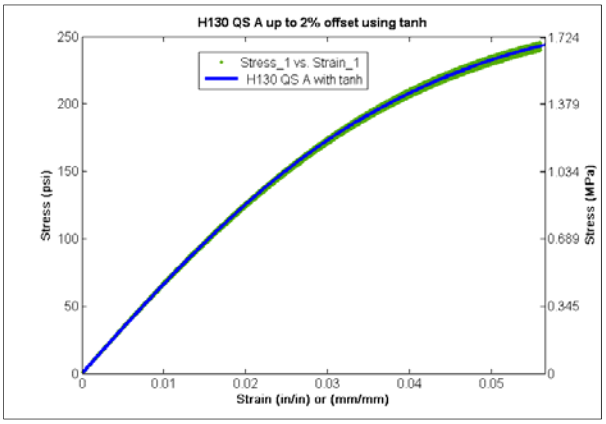
Note: The x-axis (strain) and y-axis (stress) scales are different for each plot



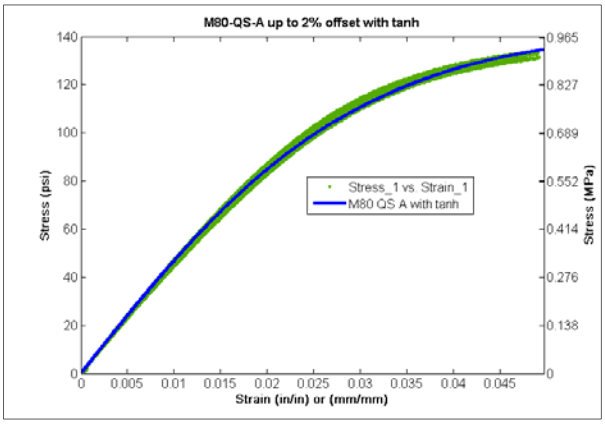
a)



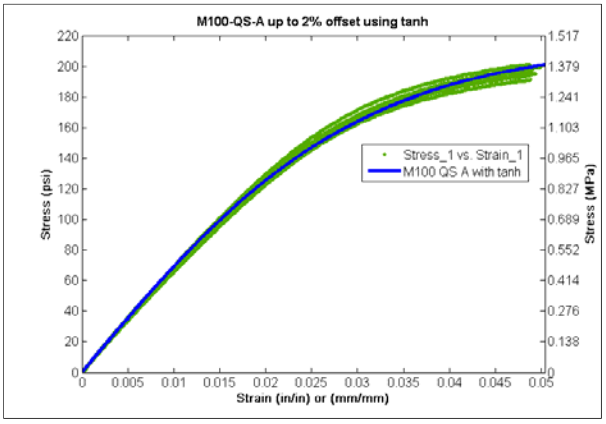
b)



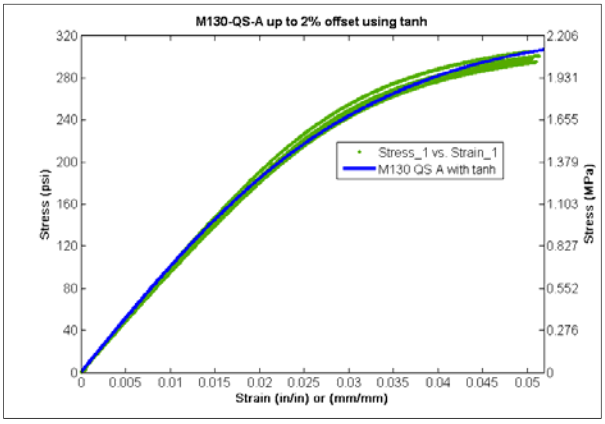
c)



d)



e)



f)

Figure J2. Model curve-fit for the quasi-static speed, standard temperature C273 tests: a) H80 core, b) H100 core, c) H130 core, d) M80 core, e) M100 core, f) M130 core.

Note: The x-axis (strain) and y-axis (stress) scales are different for each plot

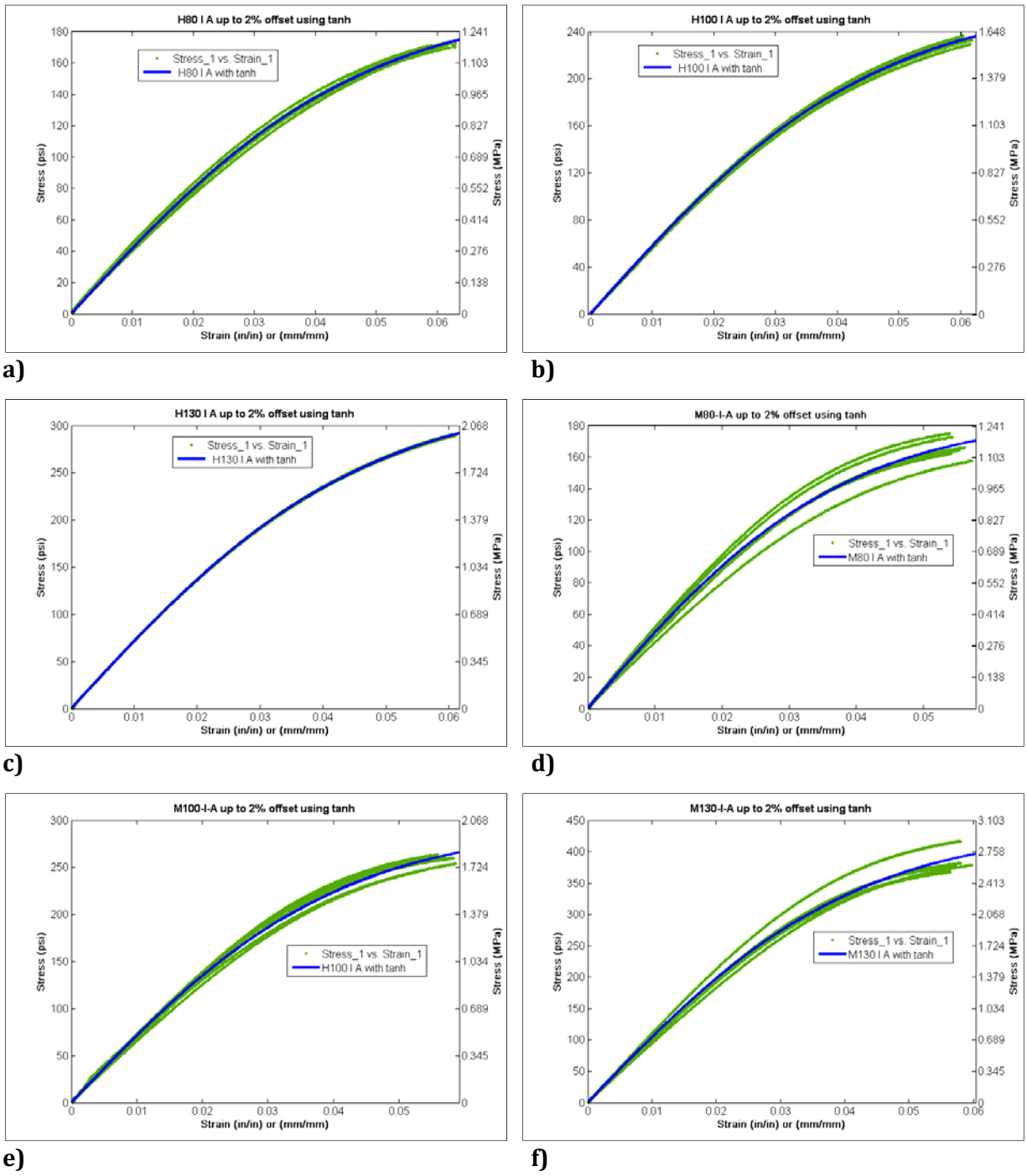


Figure J3. Model curve-fit for the intermediate speed, standard temperature C273 tests: a) H80 core, b) H100 core, c) H130 core, d) M80 core, e) M100 core, f) M130 core.

Note: The x-axis (strain) and y-axis (stress) scales are different for each plot

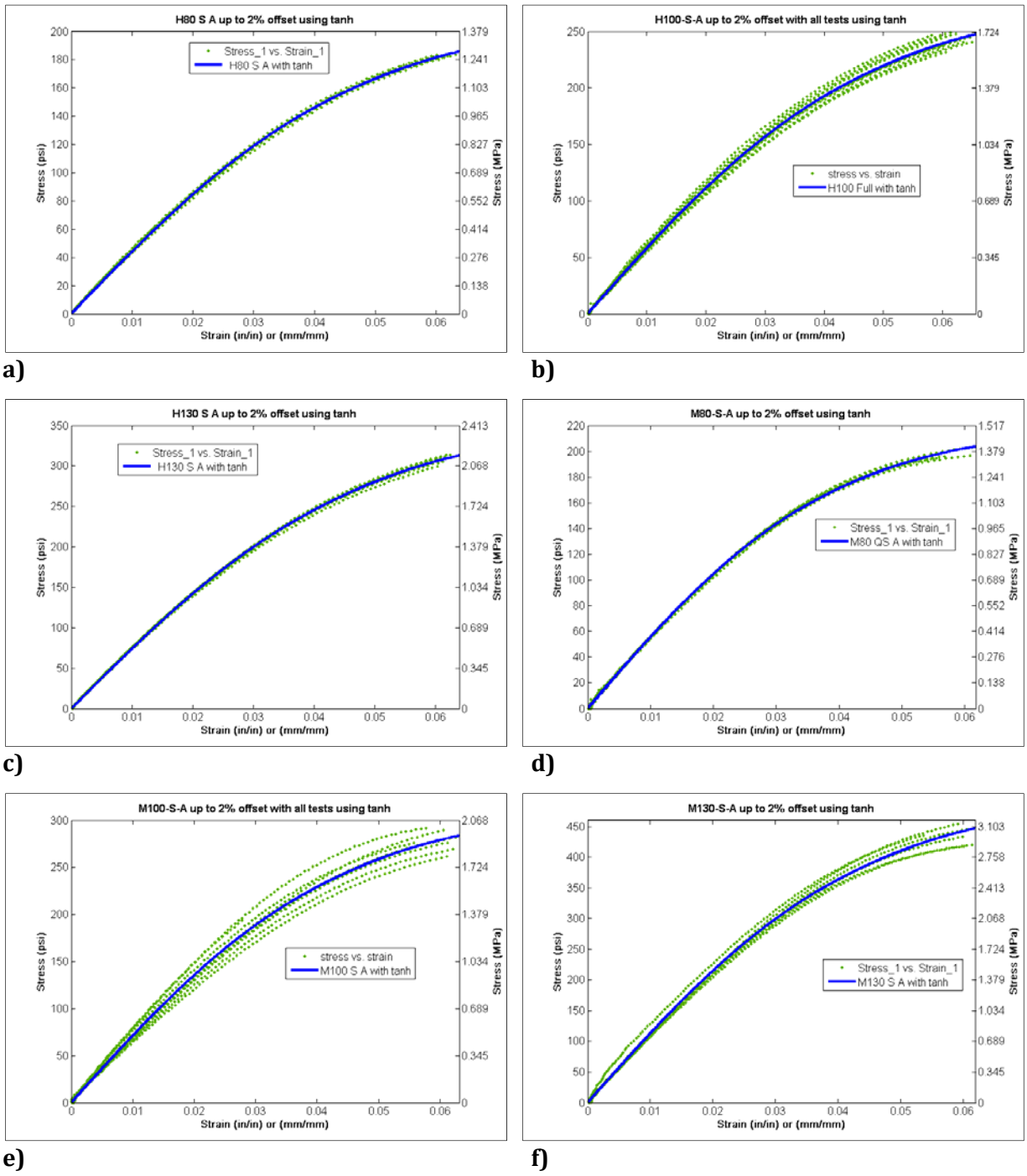
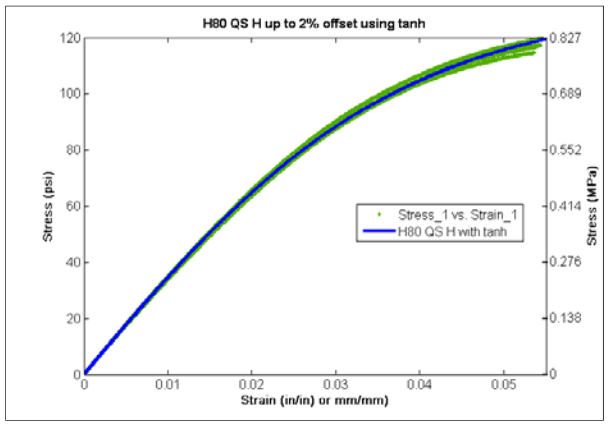
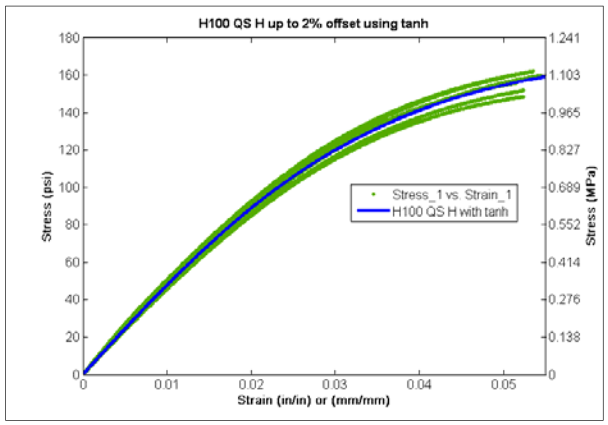


Figure J4. Model curve-fit for the slamming speed, standard temperature C273 tests: a) H80 core, b) H100 core, c) H130 core, d) M80 core, e) M100 core, f) M130 core.

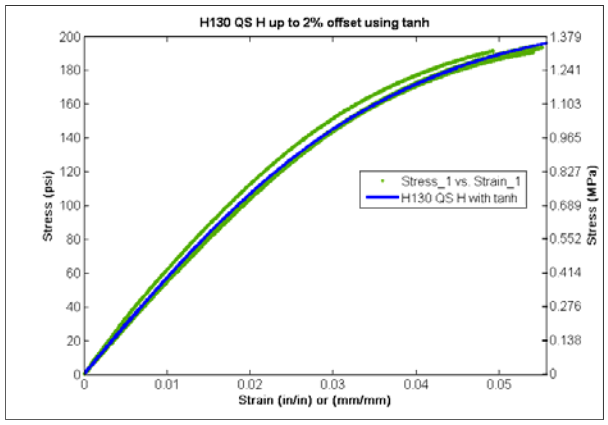
Note: The x-axis (strain) and y-axis (stress) scales are different for each plot



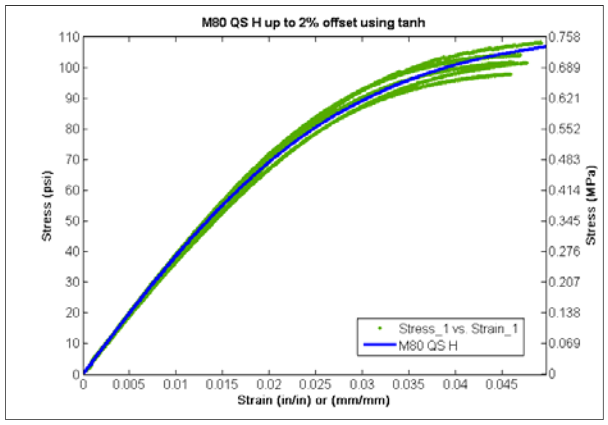
a)



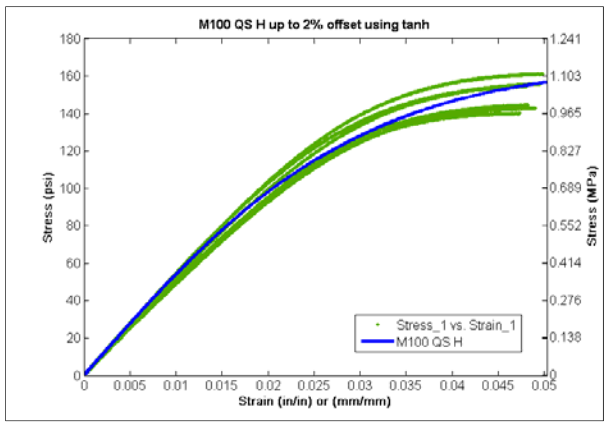
b)



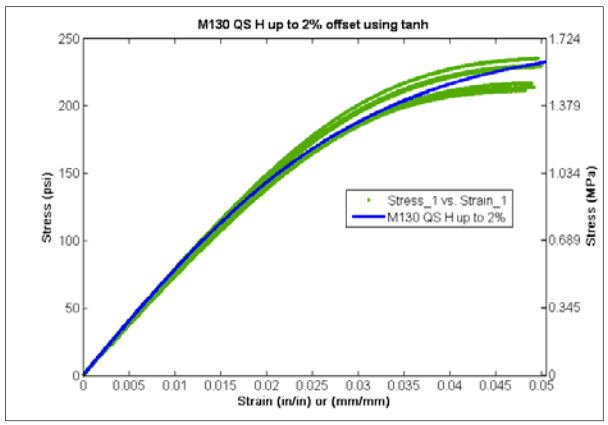
c)



d)



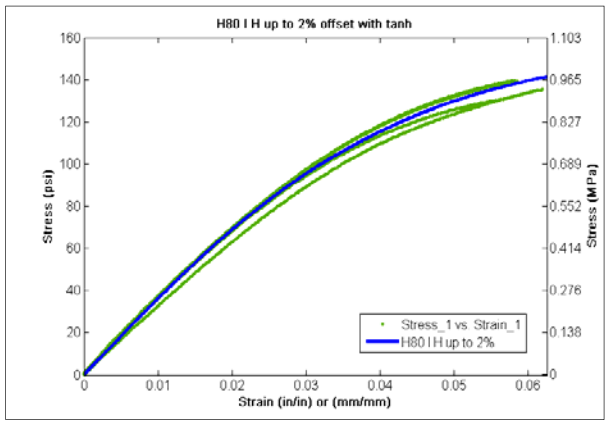
e)



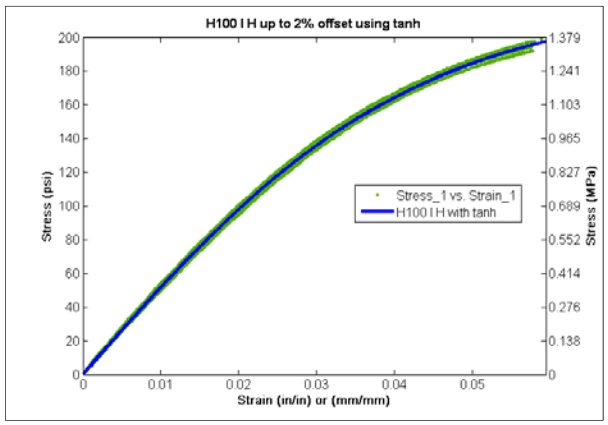
f)

Figure J5. Model curve-fit for the quasi-static speed, high temperature C273 tests: a) H80 core, b) H100 core, c) H130 core, d) M80 core, e) M100 core, f) M130 core.

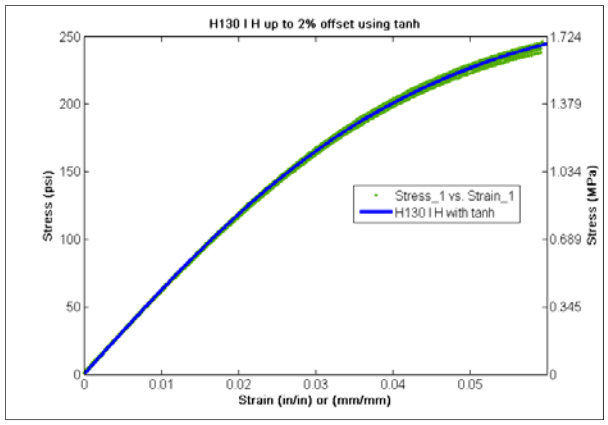
Note: The x-axis (strain) and y-axis (stress) scales are different for each plot



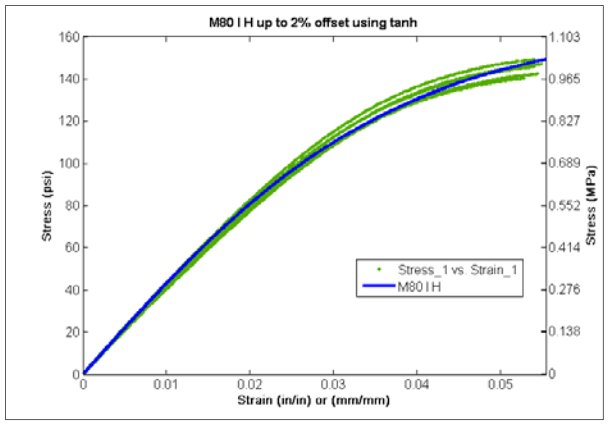
a)



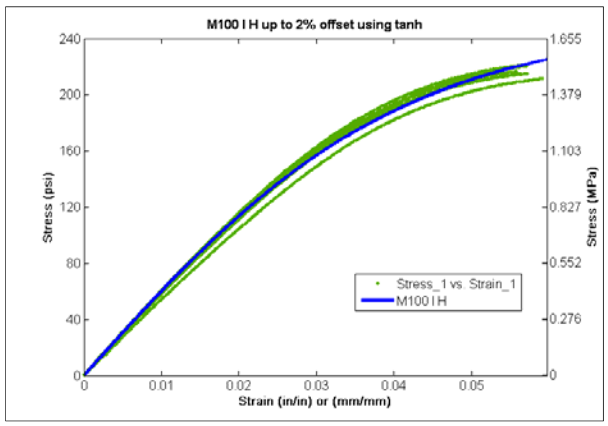
b)



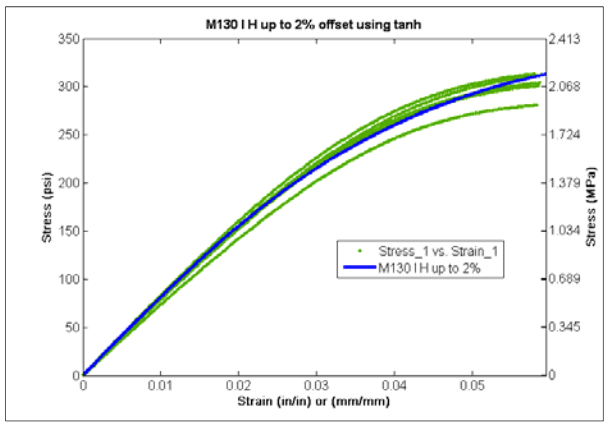
c)



d)



e)



f)

Figure J6. Model curve-fit for the intermediate speed, high temperature C273 tests: a) H80 core, b) H100 core, c) H130 core, d) M80 core, e) M100 core, f) M130 core.

Note: The x-axis (strain) and y-axis (stress) scales are different for each plot

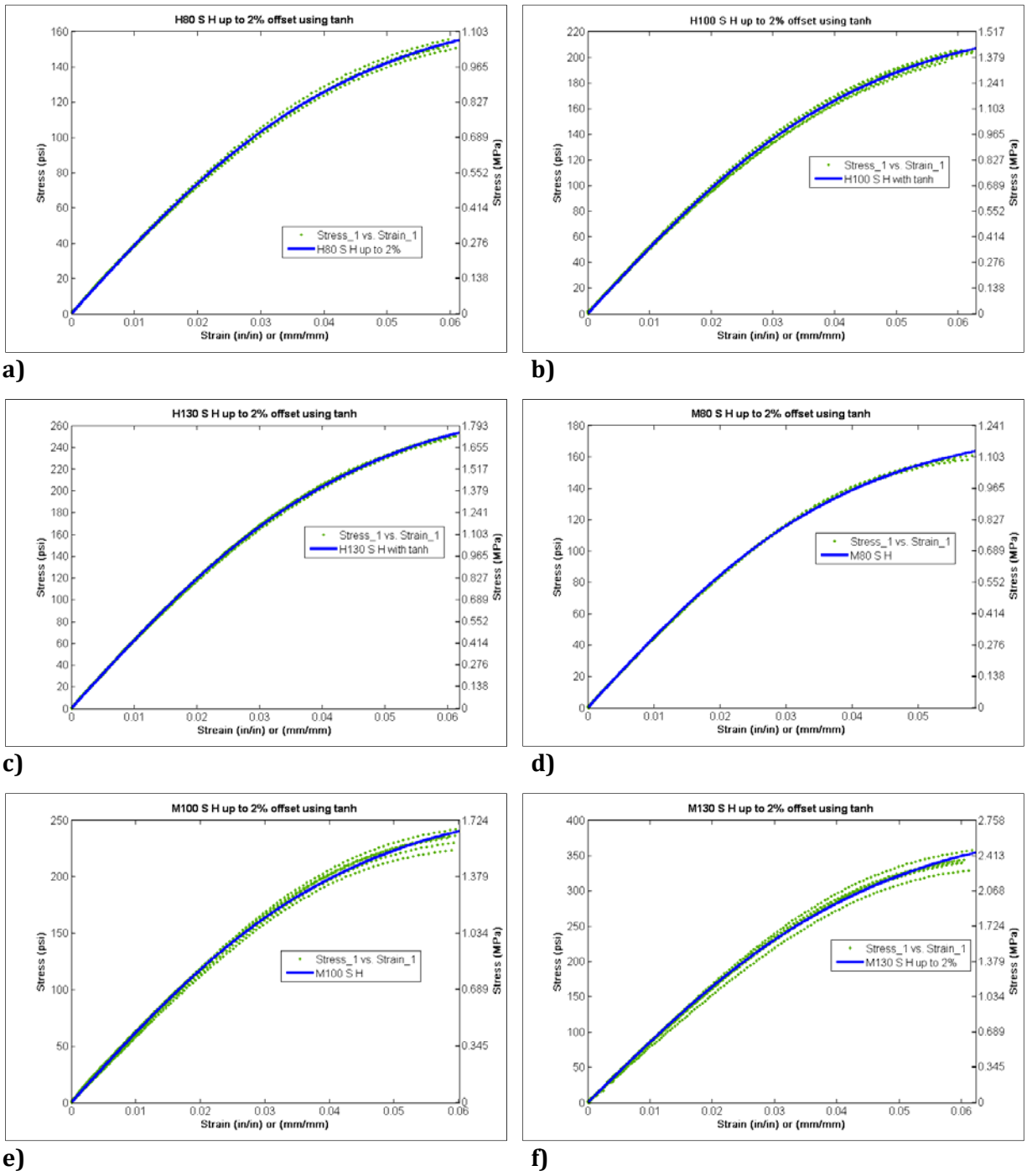


Figure J7. Model curve-fit for the slamming speed, high temperature C273 tests: a) H80 core, b) H100 core, c) H130 core, d) M80 core, e) M100 core, f) M130 core.

Note: The x-axis (strain) and y-axis (stress) scales are different for each plot

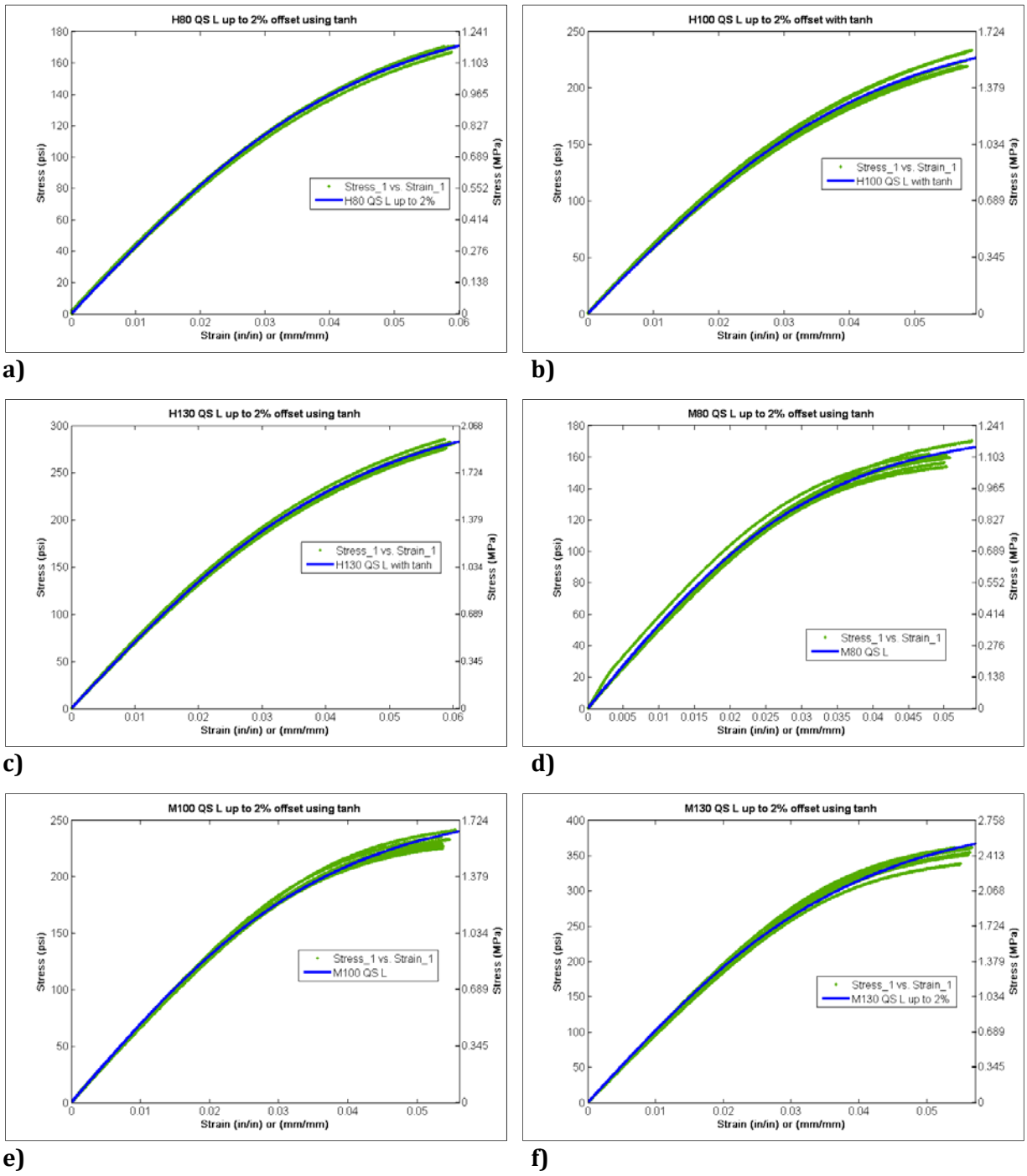


Figure J8. Model curve-fit for the quasi-static speed, low temperature C273 tests: a) H80 core, b) H100 core, c) H130 core, d) M80 core, e) M100 core, f) M130 core.

Note: The x-axis (strain) and y-axis (stress) scales are different for each plot

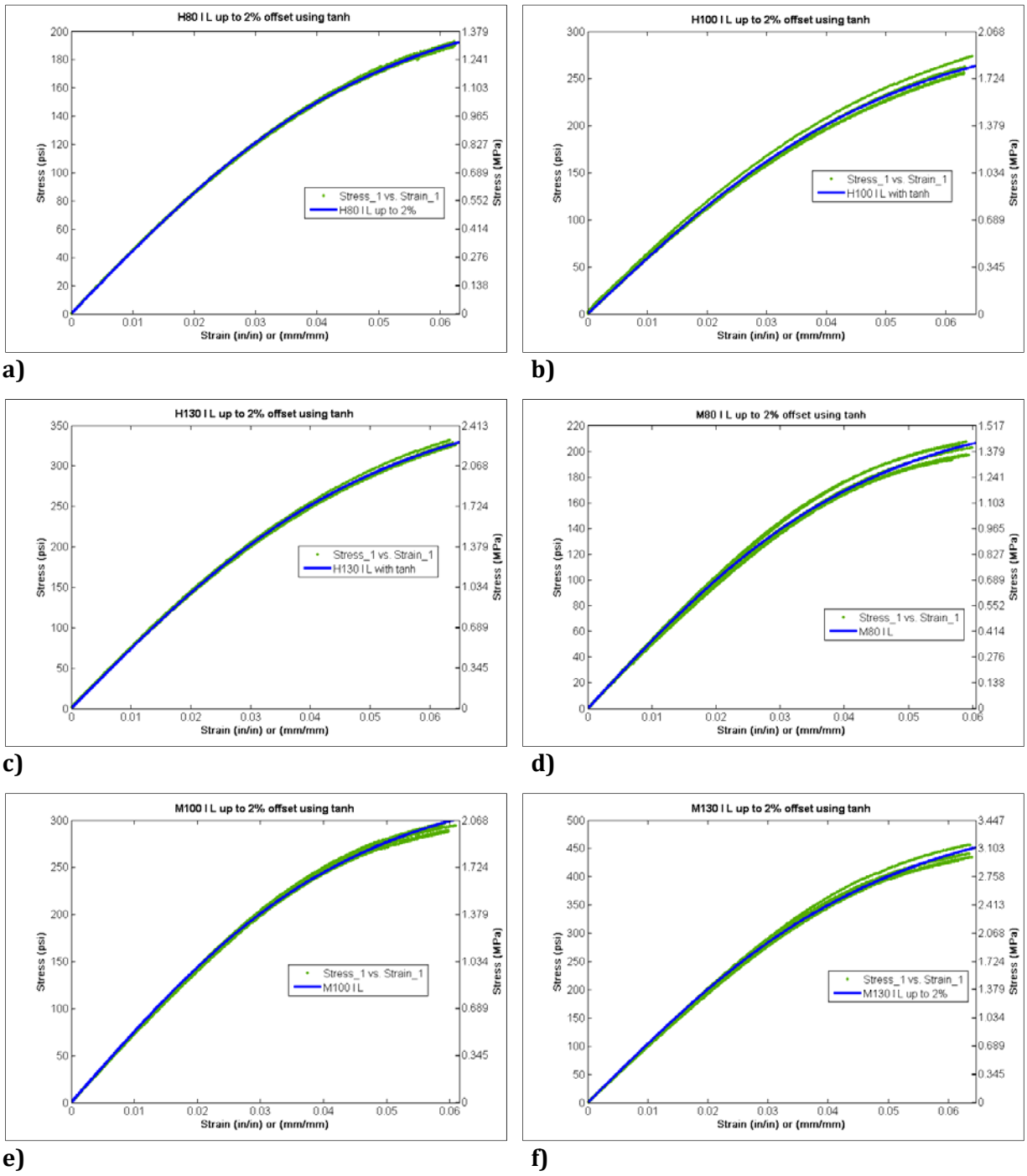
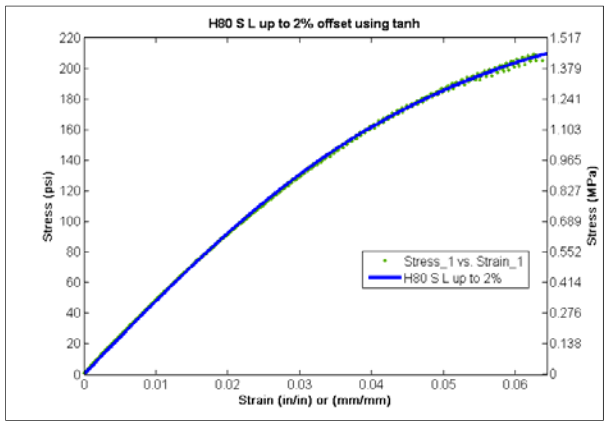
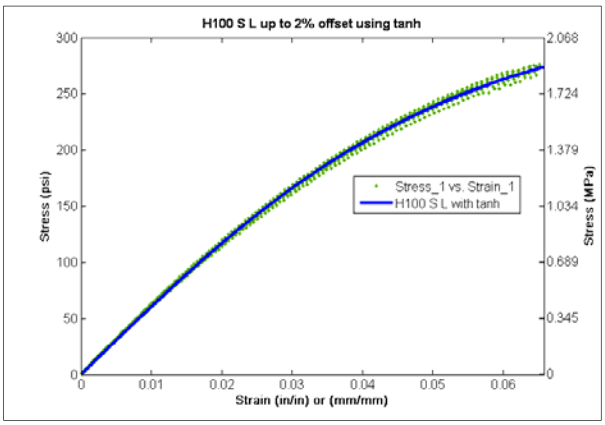


Figure J9. Model curve-fit for the intermediate speed, low temperature C273 tests: a) H80 core, b) H100 core, c) H130 core, d) M80 core, e) M100 core, f) M130 core.

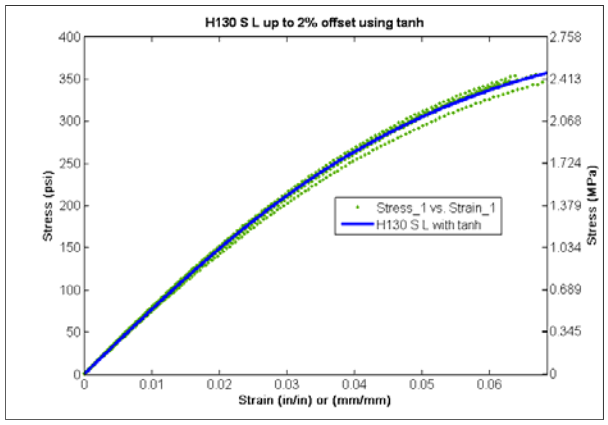
Note: The x-axis (strain) and y-axis (stress) scales are different for each plot



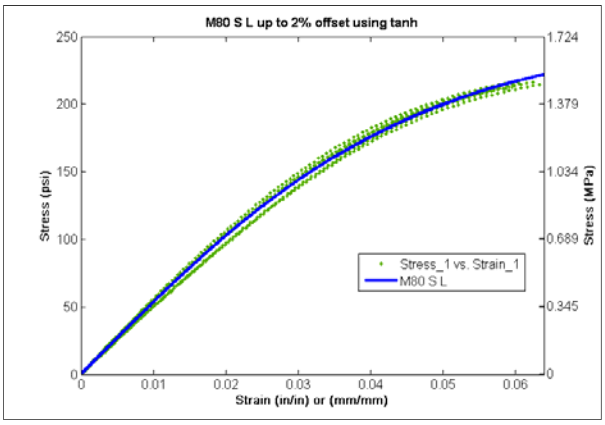
a)



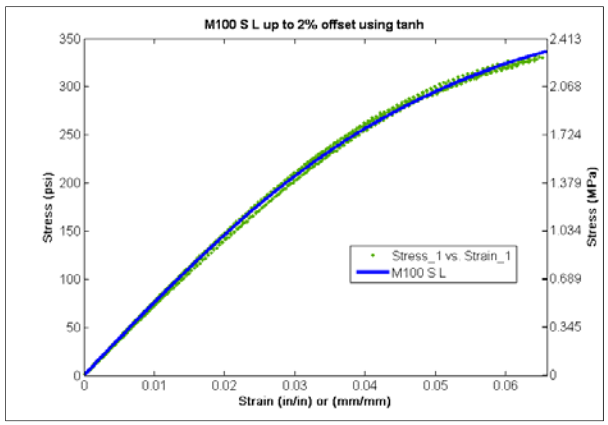
b)



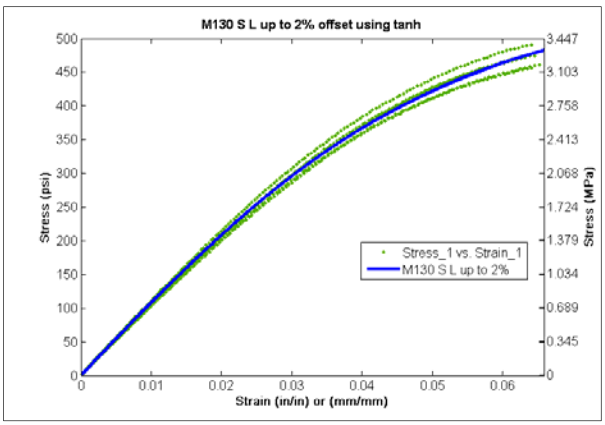
c)



d)



e)



f)

Figure J10. Model curve-fit for the slamming speed, low temperature C273 tests: a) H80 core, b) H100 core, c) H130 core, d) M80 core, e) M100 core, f) M130 core.

J4. Curve-fit parameters for the C273 tests up to the 2% offset

The curve fit parameters presented in Tables J1a through J3b were created using Matlab's curve fit tool. The data from the C273 tests was curve fit to the following function:

$$\tau = \tau_{\max} \tanh\left(\frac{G\gamma}{\tau_{\max}}\right) \qquad \textbf{(J10)}$$

where:

τ is the shear stress

γ is the shear strain

τ_{max} is a curve fit parameter representing the asymptote of the hyperbolic tangent function

G is a curve fit parameter representing the slope of the hyperbolic tangent function at the origin (0, 0).

The curve fit is used in Module 3 of the Matlab code.

Table J1a: Curve fit parameters, 2% offset, Standard Temperature (21°C) (SI units)

Core Type	Quasi-Static Speed			Intermediate Speed			Slamming Speed		
	G (MPa)	τ_{max} (MPa)	R^2	G (MPa)	τ_{max} (MPa)	R^2	G (MPa)	τ_{max} (MPa)	R^2
H80	28.66	1.178	0.9981	29.08	1.382	0.9985	30.85	1.470	0.9994
H100	37.08	1.503	0.9970	40.13	1.863	0.9992	40.71	1.938	0.9974
H130	46.69	1.906	0.9997	49.99	2.311	1.0000	51.72	2.481	0.9995
M80	33.52	0.9977	0.9985	34.09	1.291	0.9879	39.22	1.529	0.9994
M100	49.41	1.487	0.9979	50.15	2.046	0.9961	49.91	2.189	0.9920
M130	71.64	2.286	0.9982	73.36	3.052	0.9931	79.15	3.471	0.9962

Table J1b: Curve fit parameters, 2% offset, Standard Temperature (70°F) (English units)

Core Type	Quasi-Static Speed			Intermediate Speed			Slamming Speed		
	G (psi)	τ_{max} (psi)	R^2	G (psi)	τ_{max} (psi)	R^2	G (psi)	τ_{max} (psi)	R^2
H80	4157	170.9	0.9981	4218	200.5	0.9985	4475	213.2	0.9994
H100	5378	218.0	0.9970	5821	270.2	0.9992	5905	281.1	0.9974
H130	6772	276.4	0.9997	7251	335.2	1.0000	7501	359.8	0.9995
M80	4861	144.7	0.9985	4944	187.3	0.9879	5688	221.8	0.9994
M100	7166	215.7	0.9979	7273	296.8	0.9961	7239	317.5	0.9920
M130	10390	331.6	0.9982	10640	442.6	0.9931	11480	503.4	0.9962

Table J2a: Curve fit parameters, 2% offset, High Temperature (60°C) (SI units)

Core Type	Quasi-Static Speed			Intermediate Speed			Slamming Speed		
	G (MPa)	τ_{max} (MPa)	R^2	G (MPa)	τ_{max} (MPa)	R^2	G (MPa)	τ_{max} (MPa)	R^2
H80	24.44	0.9149	0.9992	25.41	1.084	0.9966	27.12	1.217	0.9994
H100	33.76	1.202	0.9956	36.29	1.539	0.9992	35.82	1.611	0.9994
H130	40.37	1.492	0.9979	43.62	1.925	0.9996	43.63	1.997	0.9998
M80	27.70	0.7812	0.9956	30.41	1.142	0.9979	31.52	1.252	0.9997
M100	38.62	1.160	0.9899	42.26	1.729	0.9972	43.46	1.873	0.9984
M130	55.99	1.731	0.9951	57.36	2.438	0.9953	59.96	2.808	0.9979

Table J2b: Curve fit parameters, 2% offset, High Temperature (140°F) (English units)

Core Type	Quasi-Static Speed			Intermediate Speed			Slamming Speed		
	G (psi)	τ_{max} (psi)	R^2	G (psi)	τ_{max} (psi)	R^2	G (psi)	τ_{max} (psi)	R^2
H80	3545	132.7	0.9992	3686	157.2	0.9966	3933	176.5	0.9994
H100	4897	174.3	0.9956	5264	223.2	0.9992	5195	233.7	0.9994
H130	5855	216.4	0.9979	6327	279.2	0.9996	6328	289.6	0.9998
M80	4018	113.3	0.9956	4410	165.6	0.9979	4571	181.6	0.9997
M100	5602	168.3	0.9899	6130	250.7	0.9972	6303	271.7	0.9984
M130	8121	251.1	0.9951	8319	353.6	0.9953	8696	407.3	0.9979

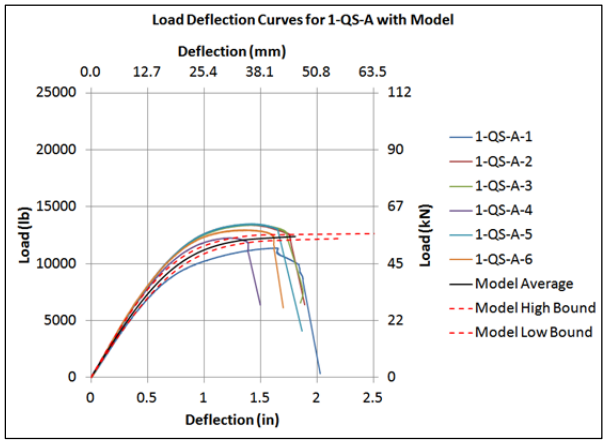
Table J3a: Curve fit parameters, 2% offset, Low Temperature (-12°C) (SI units)

Core Type	Quasi-Static Speed			Intermediate Speed			Slamming Speed		
	G (MPa)	τ_{max} (MPa)	R^2	G (MPa)	τ_{max} (MPa)	R^2	G (MPa)	τ_{max} (MPa)	R^2
H80	30.03	1.354	0.9994	31.11	1.558	0.9998	33.46	1.689	0.9998
H100	40.73	1.785	0.9978	41.29	2.133	0.9981	42.11	2.228	0.9993
H130	49.25	2.235	0.9992	51.67	2.666	0.9996	53.55	2.876	0.9990
M80	37.80	1.231	0.9955	36.76	1.618	0.9974	37.49	1.735	0.9983
M100	49.08	1.826	0.9979	52.88	2.363	0.9991	52.90	2.702	0.9993
M130	71.77	2.817	0.9974	72.88	3.606	0.9986	75.50	3.881	0.9980

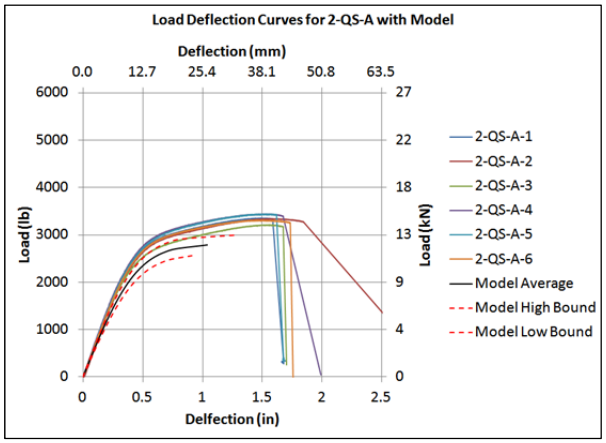
Table J3b: Curve fit parameters, 2% offset, Low Temperature (10°F) (English units)

Core Type	Quasi-Static Speed			Intermediate Speed			Slamming Speed		
	G (psi)	τ_{max} (psi)	R^2	G (psi)	τ_{max} (psi)	R^2	G (psi)	τ_{max} (psi)	R^2
H80	4355	196.4	0.9994	4512	225.9	0.9998	4853	244.9	0.9998
H100	5908	258.9	0.9978	5989	309.3	0.9981	6107	323.2	0.9993
H130	7143	324.1	0.9992	7494	386.7	0.9996	7767	417.1	0.9990
M80	5483	178.6	0.9955	5332	234.6	0.9974	5438	251.7	0.9983
M100	7119	264.8	0.9979	7669	342.7	0.9991	7673	391.9	0.9993
M130	10410	408.5	0.9974	10570	523.0	0.9986	10950	562.9	0.9980

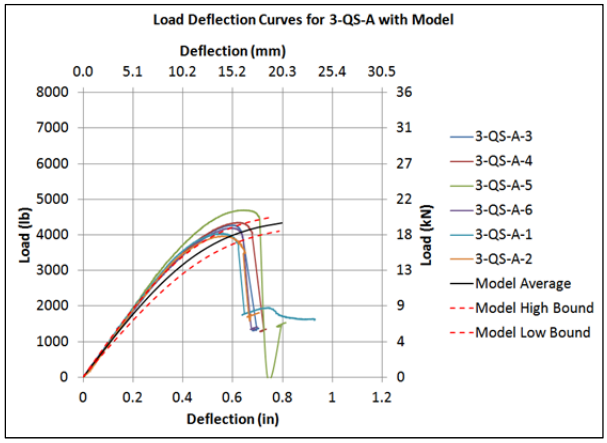
J5. The Model results compared to the C393 Experimental results



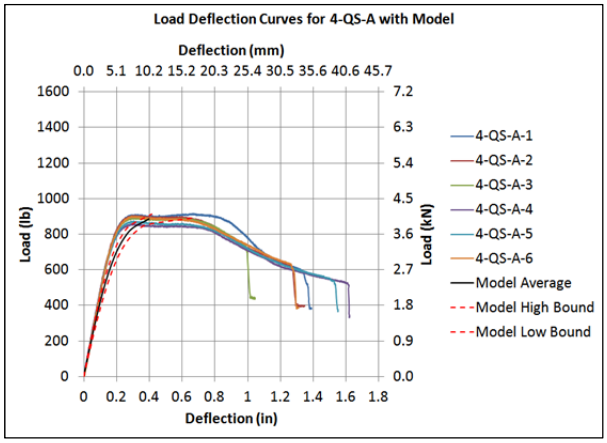
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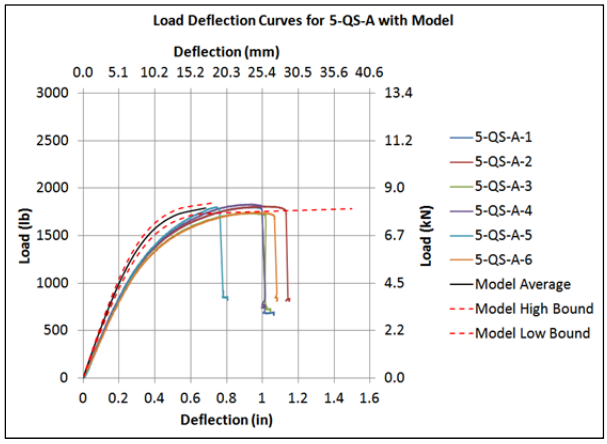
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c)

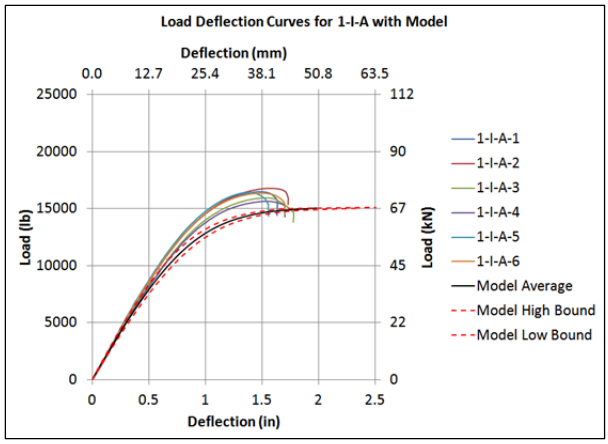


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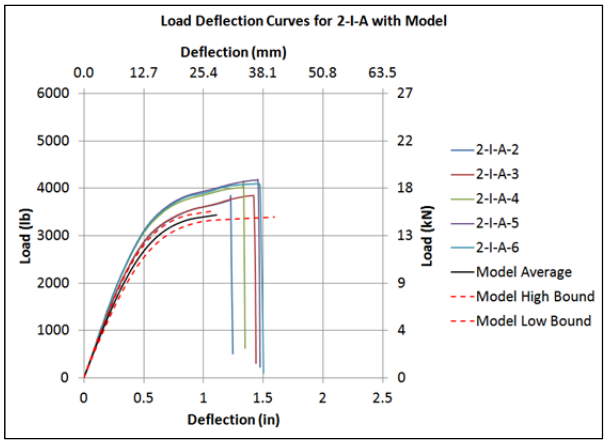


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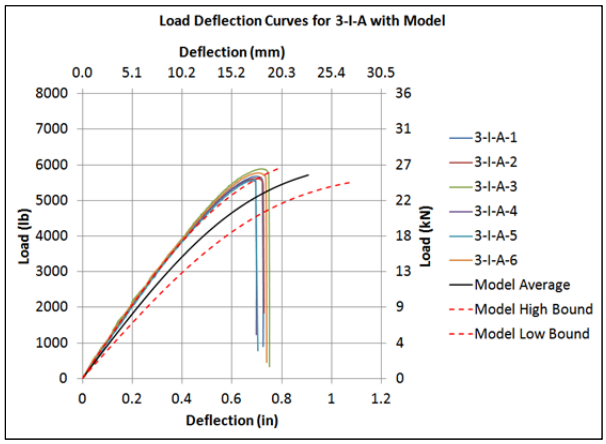
Figure J11. P-δ Curves for Quasi static speed and standard temperature with the model: a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.



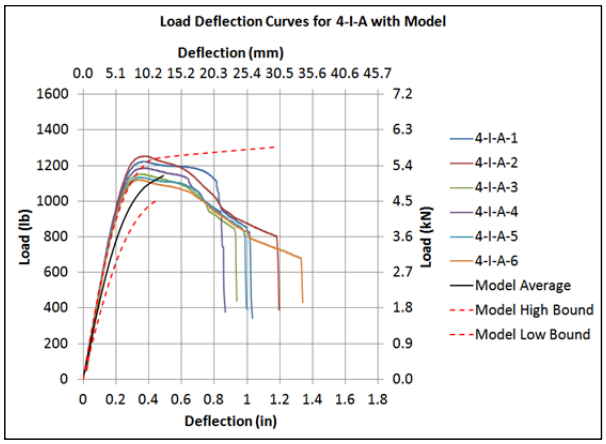
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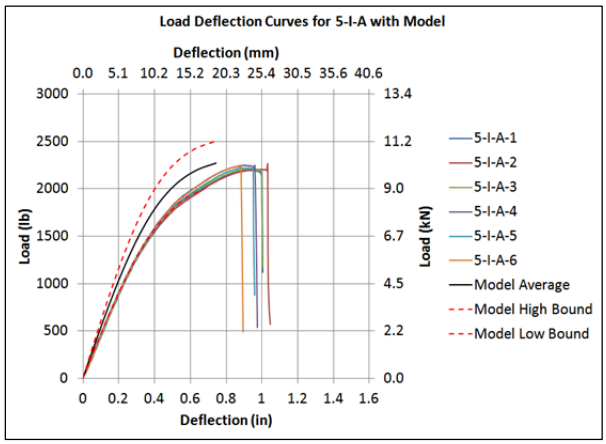
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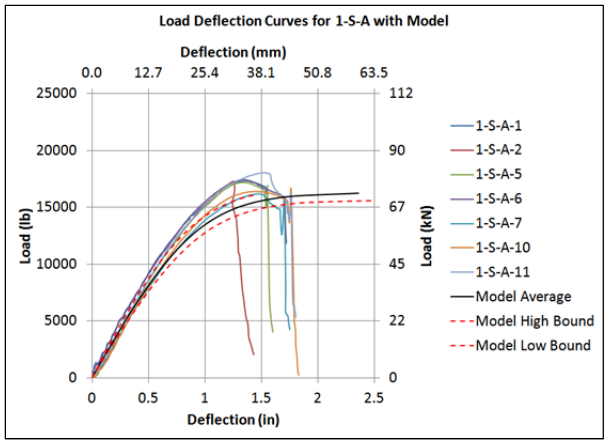


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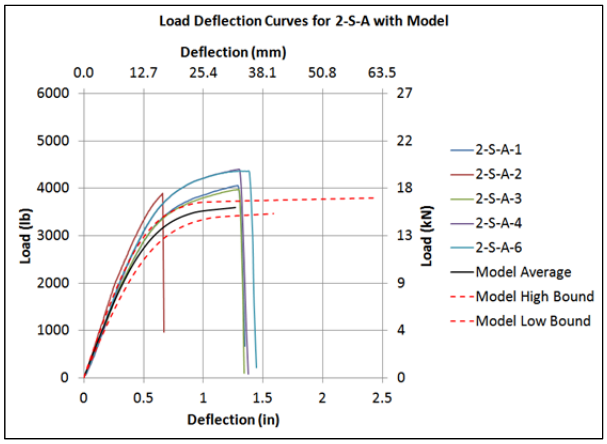


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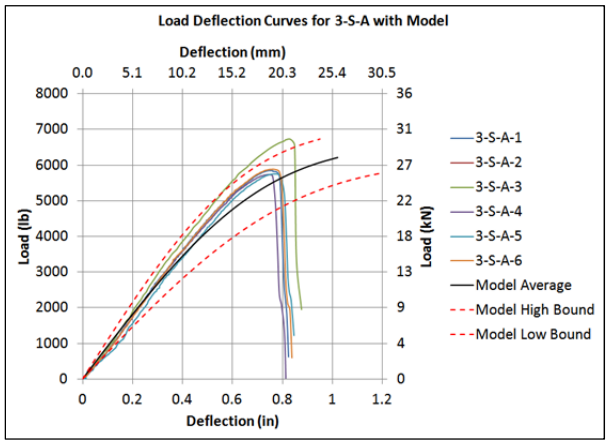
Figure J12. P-δ Curves for Intermediate speed and standard temperature with the model: a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.



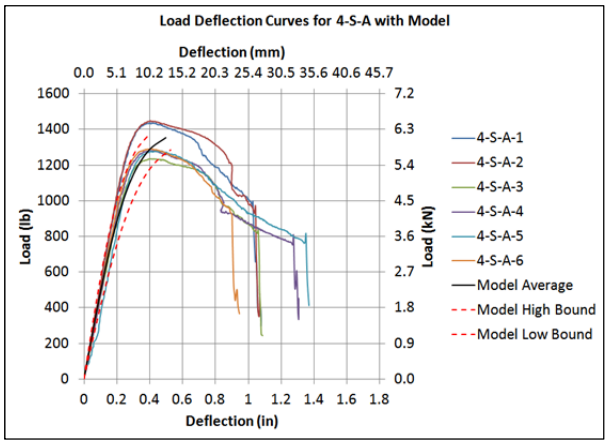
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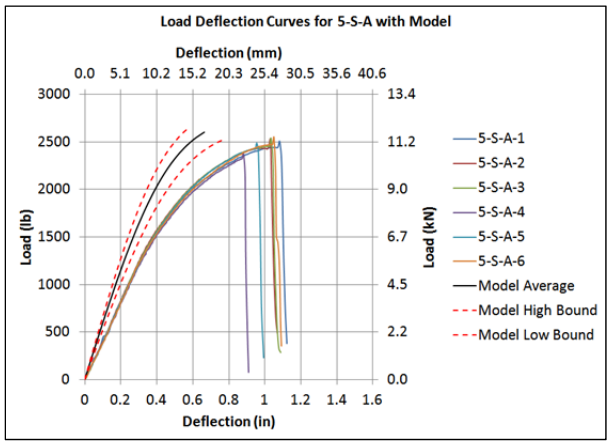
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c)

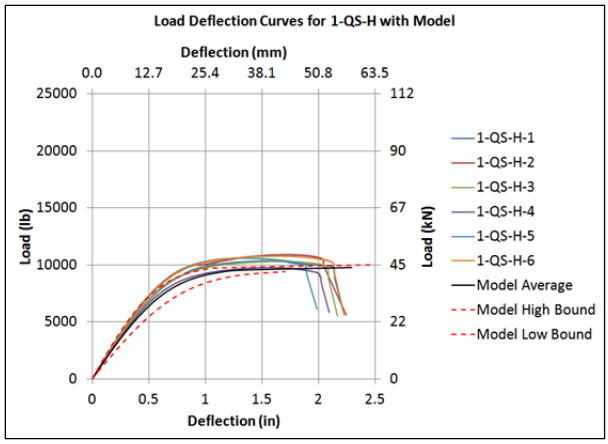


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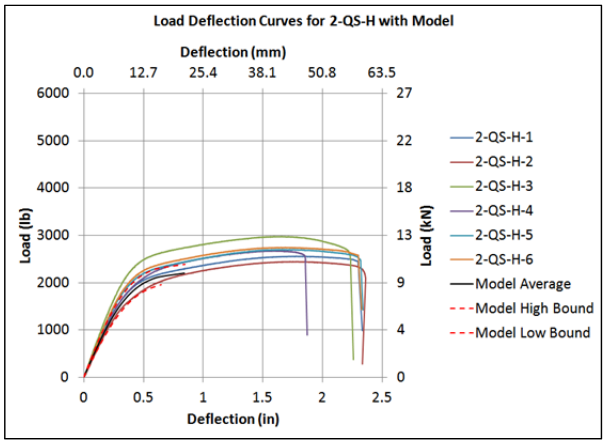


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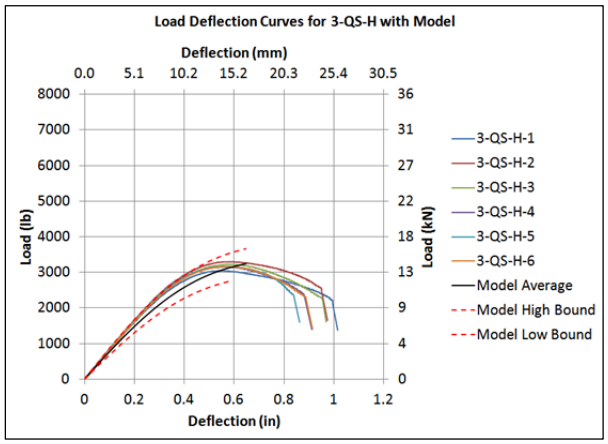
Figure J13. P-δ Curves for Slamming speed and standard temperature with the model: a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.



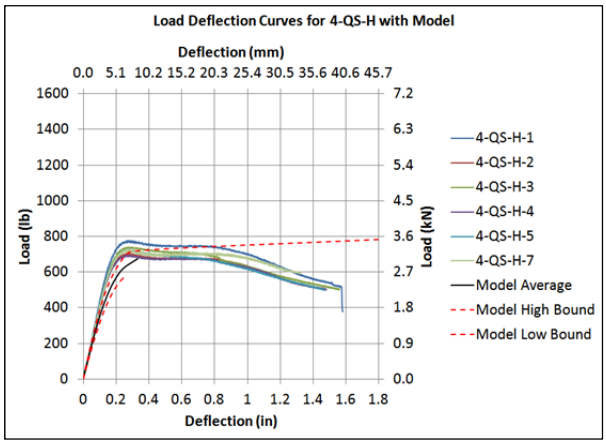
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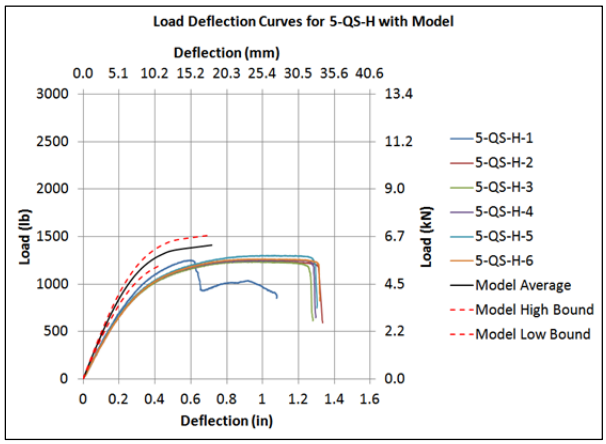
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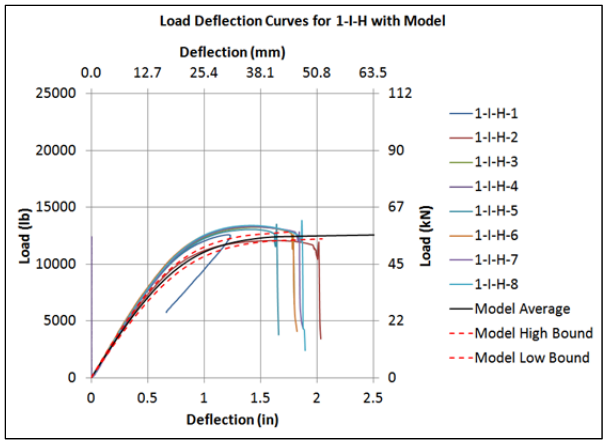


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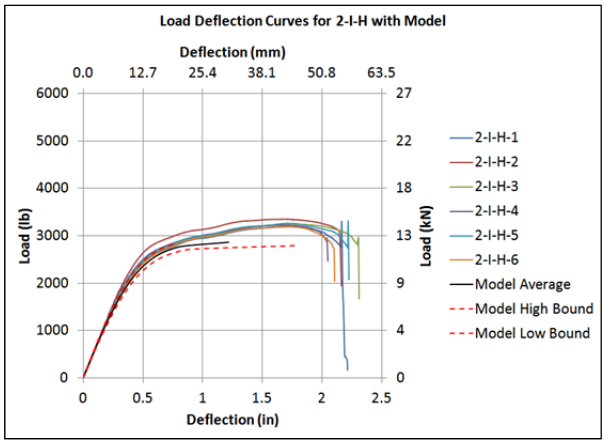


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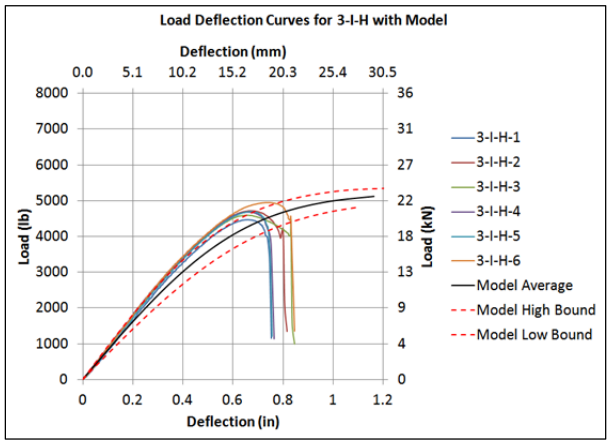
Figure J14. P-δ Curves for Quasi-static speed and high temperature with the model results: a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.



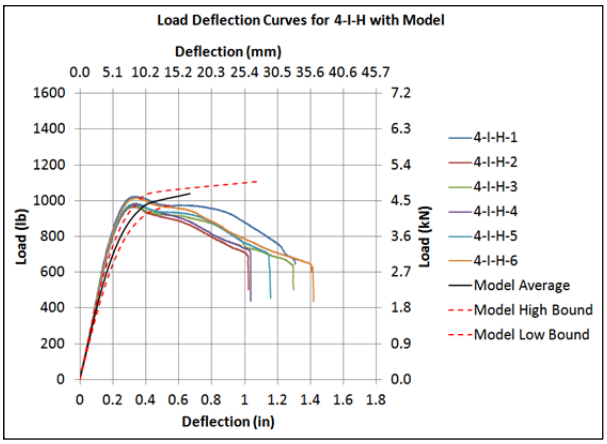
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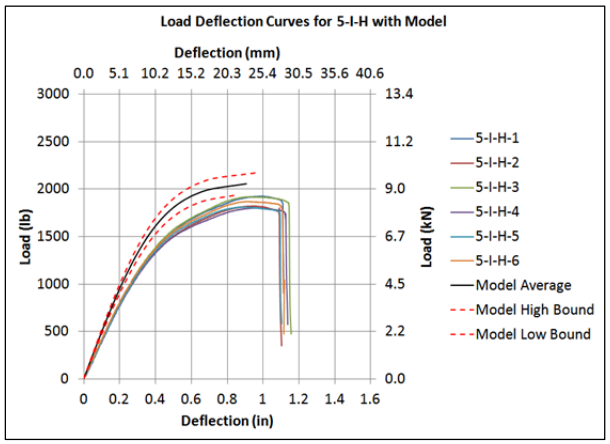
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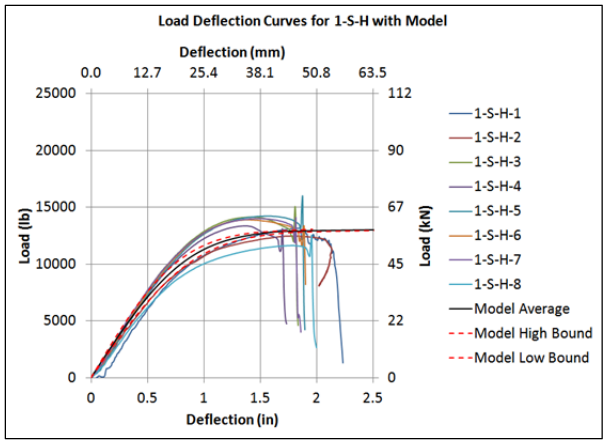


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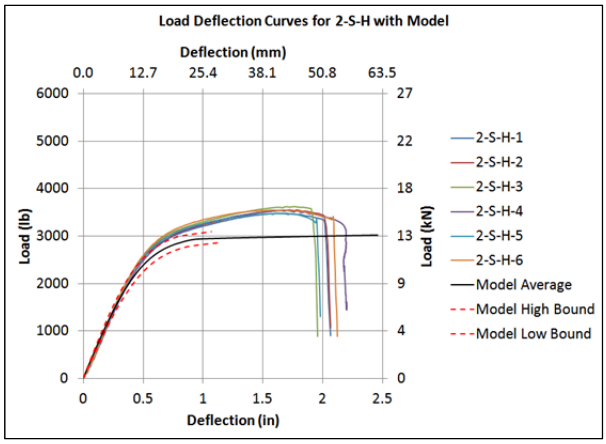


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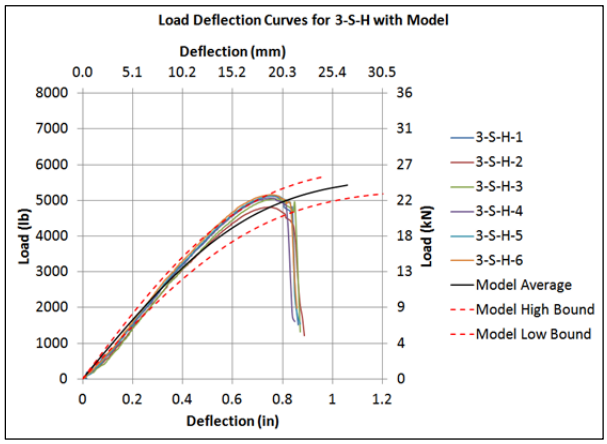
Figure J15. P-δ Curves for Intermediate speed and high temperature with the model results: a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.



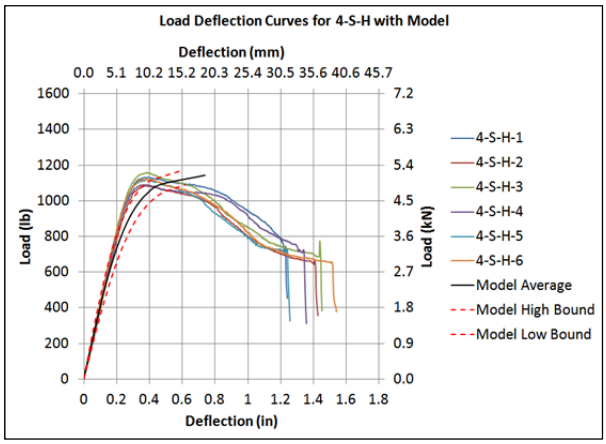
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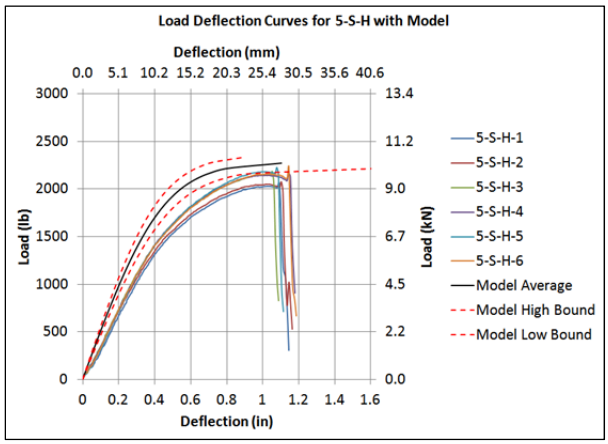
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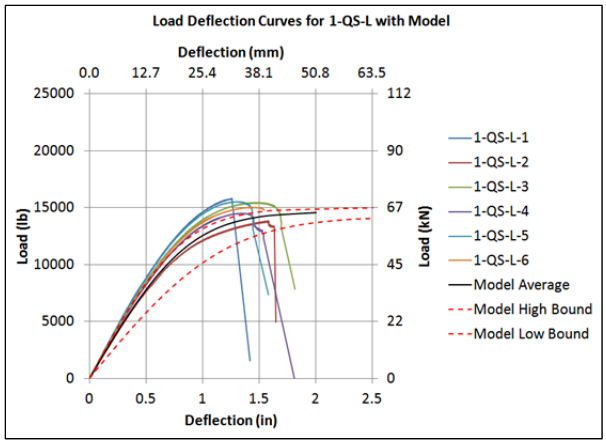


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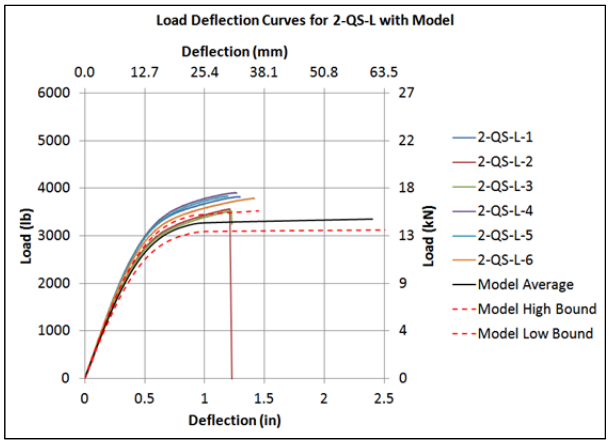


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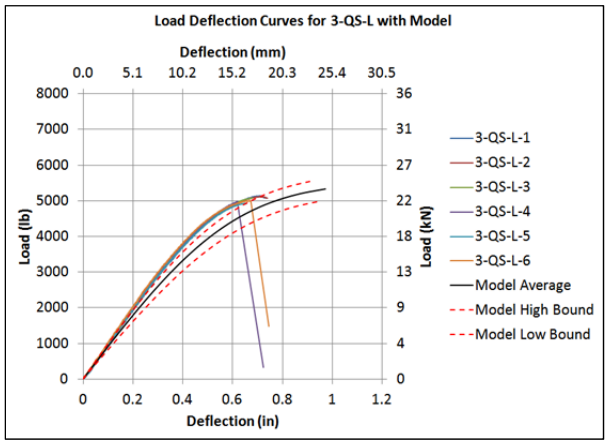
Figure J16. P-δ Curves for Slamming speed and high temperature with the model results: a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.



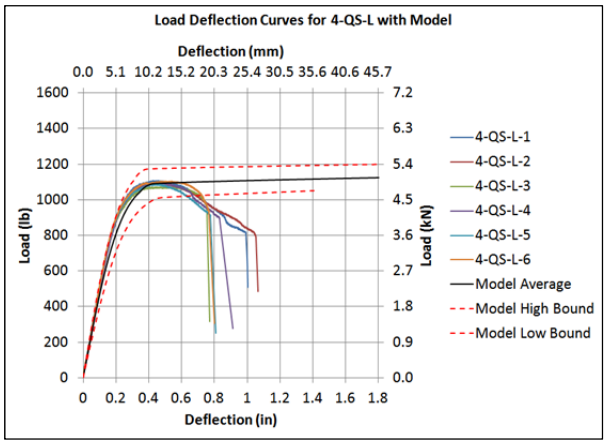
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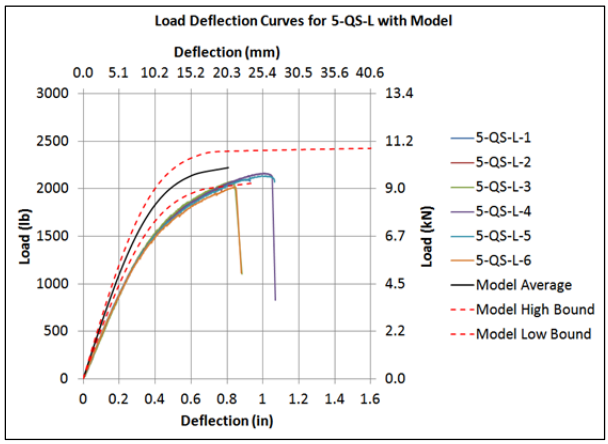
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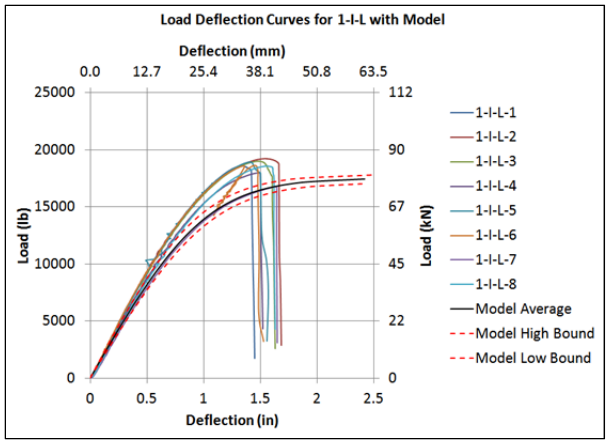


d)

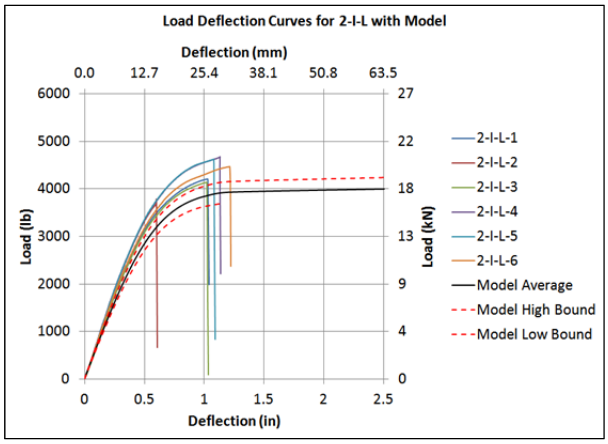


e)

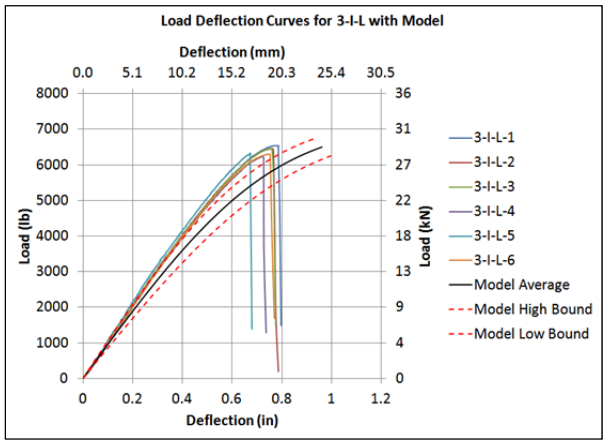
Figure J17. P-δ Curves for Quasi-static speed and low temperature with the model: a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.



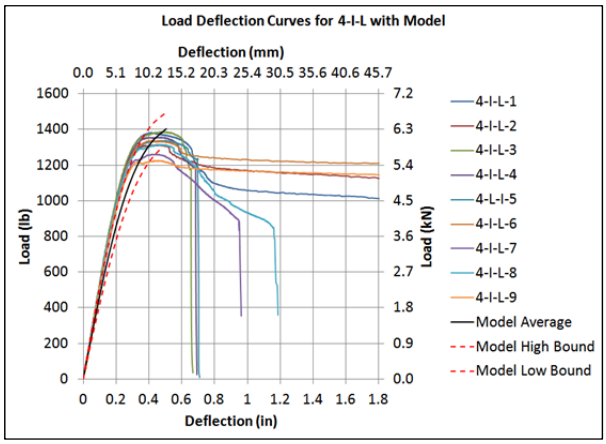
a)



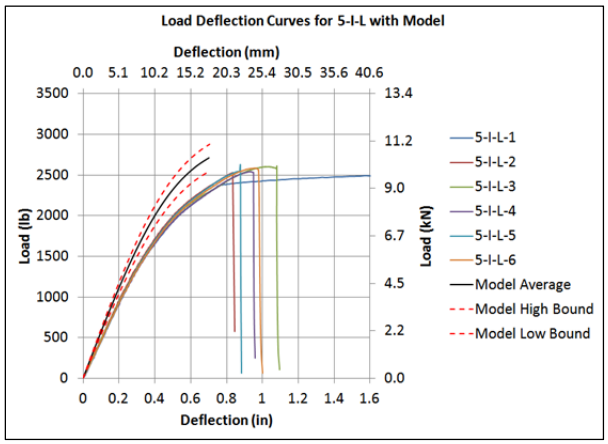
b)



c)

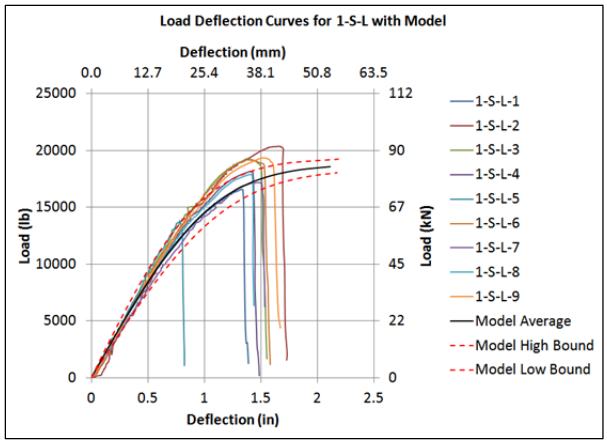


d)

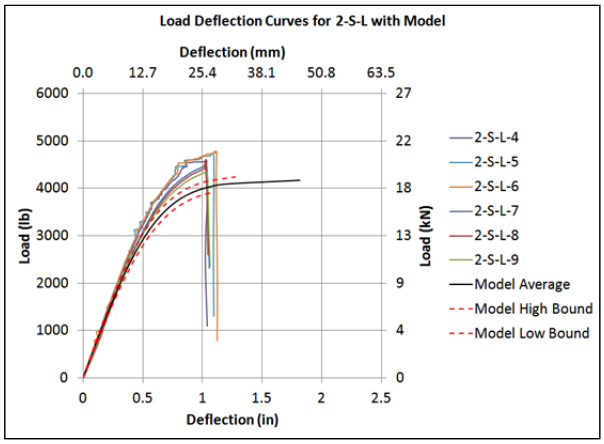


e)

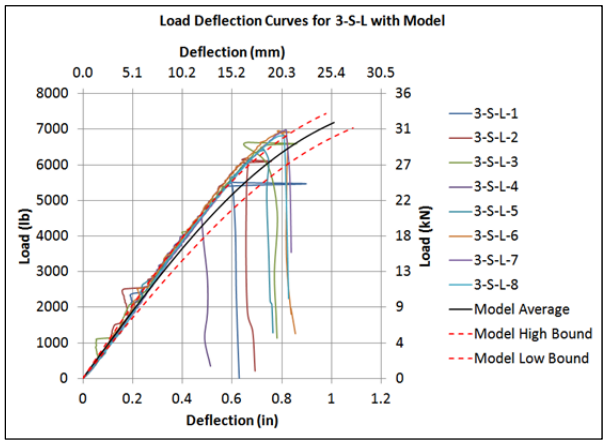
Figure J18. P-δ Curves for Intermediate speed and low temperature with the model: a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.



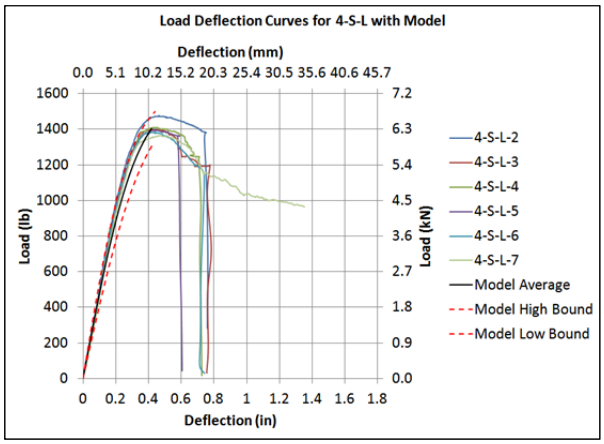
a)



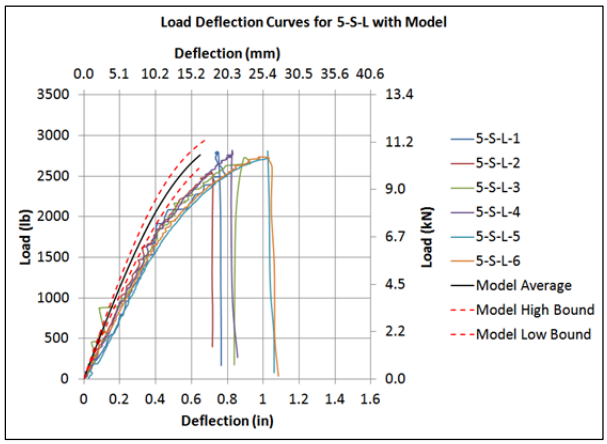
b)



c)



d)



e)

Figure J19. P-δ Curves for Slamming speed and low temperature with the model: a) Panel Type 1, b) Panel Type 2, c) Panel Type 3, d) Panel Type 4, e) Panel Type 5.

J6. Moment Curvature Model Input Data:

Tables J4 and J5 contain the modulus values and specimen dimensions, respectively, used in the Matlab code. The modulus data in Table J4 were obtained at standard temperature, but were used in the model for all temperatures. The values in Table J4 are in English units (psi). The values subscripted *t* (top skin) and *b* (bottom skin) were obtained from the material property tests on the sandwich skins. The values subscripted *c* (core) were obtained from the manufacture's data sheet. The values in Table J5 are in English units (inches) and were obtained through measurement of the test specimens, or the load span.

J4: Elastic Modulus, All Strain Rates, Standard Temperature (psi)

Panel Type	Average			High Bound			Low Bound		
	E_t	E_c	E_b	E_t	E_c	E_b	E_t	E_c	E_b
1(H130)	2640000	25375	2240000	3120551	25375	2591988	2159449	25375	2168012
2(H100)	2640000	18850	2260000	2866022	18850	2343671	2413978	18850	2176329
3(M100)	6030000	15880	3730000	7302392	15880	4213328	4757608	15880	3246672
4(M80)	5530000	10420	4700000	6970183	10420	5481815	4089817	10420	3918185
5(M80)	6070000	10420	2270000	6070000	10420	2413570	6070000	10420	2126430

J5: Beam Dimensions, All Strain Rates, All Temperatures (in.)

Panel Type	Length	Width	Thickness		
	L	*b*	*Top skin, t_t*	*Core, t_c*	*Bottom skin, t_b*
1(H130)	28	6.964	0.2373	3.009	0.2721
2(H100)	18	3.990	0.1820	1.430	0.2146
3(M100)	22	4.937	0.07575	2.027	0.1426
4(M80)	12	3.035	0.07914	0.9700	0.09656
5(M80)	17	3.983	0.05122	1.479	0.1778

J6.1 Moment Curvature Model Inputs for Standard Temperature

Tables J6 through J14 hold the curve fit parameters used in the Matlab code. The average values were obtained directly from the curve fit. The high and low bound values were created by taking the 95% confidence interval spread (difference between the high value and the average) from the C273 tests and adding to, or subtracting from, the average from the curve fit. The spread for the curve fit of G was generated from the C273 shear modulus spread, and the spread for the curve fit of τ was generated from the C273 2% offset stress spread. This was done because the 95% confidence interval values obtained from the curve fit itself were based on uncertainty in the curve fit, not in the test data. The 95% confidence interval from the C273 tests, however, was based on uncertainty in the test. All values are in English units (psi).

J6: Curve Fit Parameters, Quasi-Static Speed, Standard Temperature (psi)

Panel Type	Average		High Bound		Low Bound	
	τ	G	τ	G	τ	G
1(H130)	276.4	6772	282.3	6950	270.5	6594
2(H100)	218.0	5378	233.3	5768	202.7	4988
3(M100)	215.7	7166	224.9	7529	206.5	6803
4(M80)	144.7	4861	148.3	5177	141.1	4545
5(M80)	144.7	4861	148.3	5177	141.1	4545

J7: Curve Fit Parameters, Intermediate Speed, Standard Temperature (psi)

Panel Type	Average		High Bound		Low Bound	
	τ	G	τ	G	τ	G
1(H130)	335.2	7251	337.5	7460	332.9	7042
2(H100)	270.2	5821	277.5	6222	262.9	5421
3(M100)	296.8	7273	314.5	8175	279.1	6371
4(M80)	187.3	4944	204.3	5791	170.3	4097
5(M80)	187.3	4944	204.3	5791	170.3	4097

J8: Curve Fit Parameters, Slamming Speed, Standard Temperature (psi)

Panel Type	Average		High Bound		Low Bound	
	τ	G	τ	G	τ	G
1(H130)	359.8	7501	374.2	7852	345.4	7150
2(H100)	281.1	5905	293.0	6692	269.2	5118
3(M100)	317.5	7239	341.0	8747	294.0	5731
4(M80)	221.8	5688	230.0	6634	213.6	4742
5(M80)	221.8	5688	230.0	6634	213.6	4742

J6.2 Moment Curvature Model Inputs for High Temperature

J9: Curve Fit Parameters, Quasi-Static Speed, High Temperature (psi)

Panel Type	Average		High Bound		Low Bound	
	τ	G	τ	G	τ	G
1(H130)	216.4	5855	221.4	7011	211.4	4699
2(H100)	174.3	4897	187.6	5494	161.0	4300
3(M100)	168.3	5602	190.2	6156	146.4	5048
4(M80)	113.3	4018	122.3	4336	104.3	3700
5(M80)	113.3	4018	122.3	4336	104.3	3700

J10: Curve Fit Parameters, Intermediate Speed, High Temperature (psi)

Panel Type	Average		High Bound		Low Bound	
	τ	G	τ	G	τ	G
1(H130)	279.2	6327	286.9	6519	271.5	6136
2(H100)	223.2	5264	230.8	5490	215.6	5038
3(M100)	250.7	6130	260.0	6790	241.4	5470
4(M80)	165.6	4410	174.1	4660	157.1	4160
5(M80)	165.6	4410	174.1	4660	157.1	4160

J11: Curve Fit Parameters, Slamming Speed, High Temperature (psi)

Panel Type	Average		High Bound		Low Bound	
	τ	G	τ	G	τ	G
1(H130)	289.6	6328	291.4	6660	287.8	5996
2(H100)	233.7	5195	242.6	5626	224.8	4765
3(M100)	271.7	6303	287.9	6774	255.50	5832
4(M80)	181.6	4571	187.6	5109	175.6	4033
5(M80)	181.6	4571	187.6	5109	175.6	4033

J6.3 Moment Curvature Model Inputs for Low Temperature

J12: Curve Fit Parameters, Quasi-Static Speed, Low Temperature (psi)

Panel Type	Average		High Bound		Low Bound	
	τ	G	τ	G	τ	G
1(H130)	324.1	7143	332.3	7499	315.9	4699
2(H100)	258.9	5908	274.1	6232	243.7	5584
3(M100)	264.8	7119	279.7	7426	249.9	6812
4(M80)	178.6	5483	193.0	6213	164.2	4753
5(M80)	178.6	5483	193.0	6213	164.2	4753

J13: Curve Fit Parameters, Intermediate Speed, Low Temperature (psi)

Panel Type	Average		High Bound		Low Bound	
	τ	G	τ	G	τ	G
1(H130)	386.7	7494	395.2	7747	378.2	7241
2(H100)	309.3	5989	327.2	6242	291.4	5736
3(M100)	342.7	7669	351.7	8149	333.7	7189
4(M80)	234.6	5332	248.5	5749	220.7	4916
5(M80)	234.6	5332	248.5	5749	220.7	4916

J14: Curve Fit Parameters, Slamming Speed, Low Temperature (psi)

Panel Type	Average		High Bound		Low Bound	
	τ	G	τ	G	τ	G
1(H130)	417.1	7767	427.6	8699	406.6	6836
2(H100)	323.2	6107	332.5	6371	313.9	5843
3(M100)	391.9	7673	402.2	8044	381.6	7303
4(M80)	251.7	5438	255.6	6109	247.8	4767
5(M80)	251.7	5438	255.6	6109	247.8	4767

J6.4 Stress & Strain Limits for Quasi-Static Strain Rate at Standard Temperature

Tables J15 through J23 contain the failure criteria for the Matlab code. The stress values are in English units (psi). The Top Skin and Bottom Skin values were obtained from the experimental material test data on the skins. The core values were obtained from the C273 tests.

J15a: Limits, Average, Quasi-Static Speed, Standard Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	42080	0.3250	299.8	0.02140	34150
2(H100)	0.01596	38620	0.3600	238.3	0.01555	35150
3(M100)	0.01030	53120	0.2000	203.7	0.01780	62090
4(M80)	0.01210	53280	0.4000	153.3	0.01350	60920
5(M80)	0.005700	34700	0.4000	153.3	0.01697	38520

J15b: Limits, High Bound, Quasi-Static Speed, Standard Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	45326	0.3500	321.3	0.02140	37065
2(H100)	0.01596	45739	0.3600	256.8	0.01555	36668
3(M100)	0.01030	65745	0.2000	212.7	0.01780	71333
4(M80)	0.01210	70795	0.4000	165.3	0.01350	91697
5(M80)	0.005700	34700	0.4000	156.3	0.01744	42105

J15c: Limits, Low Bound, Quasi-Static Speed, Standard Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	38834	0.3000	278.4	0.02140	31235
2(H100)	0.01305	31501	0.3600	219.9	0.01545	33632
3(M100)	0.01030	40495	0.2000	194.7	0.01780	52847
4(M80)	0.01210	35765	0.4000	141.3	0.01350	30143
5(M80)	0.005700	34700	0.40000	141.3	0.01643	34935

J6.5 Stress & Strain Limits for Intermediate Strain Rate at Standard Temperature

J16a: Limits, Average, Intermediate Speed, Standard Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	42080	0.2000	340.2	0.02140	34150
2(H100)	0.01596	38620	0.2500	274.2	0.01555	35150
3(M100)	0.01030	53120	0.2500	268.0	0.01780	62090
4(M80)	0.01210	53280	0.2500	176.1	0.01350	60920
5(M80)	0.005700	34700	0.2500	176.1	0.01697	38520

J16b: Limits, High Bound, Intermediate Speed, Standard Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	45326	0.2250	346.1	0.02140	37065
2(H100)	0.01596	45739	0.2500	290.3	0.01555	36668
3(M100)	0.01030	65745	0.2500	274.7	0.01780	71333
4(M80)	0.01210	70795	0.2500	195.6	0.01350	91697
5(M80)	0.005700	34700	0.2500	195.6	0.01744	42105

J16c: Limits, Low Bound, Intermediate Speed, Standard Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	38834	0.1750	334.3	0.02140	31235
2(H100)	0.01305	31501	0.2500	258.2	0.01545	33632
3(M100)	0.01030	40495	0.2500	261.3	0.01780	52847
4(M80)	0.01210	35765	0.2500	156.6	0.01350	30143
5(M80)	0.005700	34700	0.2500	156.6	0.01643	34935

J6.6 Stress & Strain Limits for Slamming Strain Rate at Standard Temperature

J17a: Limits, Average, Slamming Speed, Standard Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	42080	0.2000	362.2	0.02140	34150
2(H100)	0.01596	38620	0.2200	285.1	0.01555	35150
3(M100)	0.01030	53120	0.2000	292.5	0.01780	62090
4(M80)	0.01210	53280	0.3000	203.8	0.01350	60920
5(M80)	0.005700	34700	0.3000	203.8	0.01697	38520

J17b: Limits, High Bound, Slamming Speed, Standard Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	45326	0.2100	352.0	0.02140	37065
2(H100)	0.01596	45739	0.2200	303.1	0.01555	36668
3(M100)	0.01030	65745	0.2000	315.0	0.01780	71333
4(M80)	0.01210	70795	0.3000	209.2	0.01350	91697
5(M80)	0.005700	34700	0.3000	209.2	0.01744	42105

J17c: Limits, Low Bound, Slamming Speed, Standard Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	38834	0.1900	372.4	0.02140	31235
2(H100)	0.01305	31501	0.2200	267.0	0.01545	33632
3(M100)	0.01030	40495	0.2000	270.0	0.01780	52847
4(M80)	0.01210	35765	0.3000	198.4	0.01350	30143
5(M80)	0.005700	34700	0.3000	198.4	0.01643	34935

J6.7 Stress & Strain Limits for Quasi-Static Strain Rate at High Temperature

J18a: Limits, Average, Quasi-Static Speed, High Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	42080	0.5000	214.3	0.02140	34150
2(H100)	0.01596	38620	0.2000	170.3	0.01555	35150
3(M100)	0.01030	53120	0.6000	150.0	0.01780	62090
4(M80)	0.01210	53280	0.5000	117.3	0.01350	60920
5(M80)	0.005700	34700	0.5000	117.3	0.01697	38520

J18b: Limits, High Bound, Quasi-Static Speed, High Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	45326	0.5000	225.6	0.02140	37065
2(H100)	0.01596	45739	0.2000	193.6	0.01555	36668
3(M100)	0.01030	65745	0.6000	172.0	0.01780	71333
4(M80)	0.01210	70795	0.5000	144.3	0.01350	91697
5(M80)	0.005700	34700	0.5000	144.3	0.01744	42105

J18c: Limits, Low Bound, Quasi-Static Speed, High Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	38834	0.5000	203.0	0.02140	31235
2(H100)	0.01305	31501	0.2000	147.0	0.01545	33632
3(M100)	0.01030	40495	0.6000	128.0	0.01780	52847
4(M80)	0.01210	35765	0.5000	90.20	0.01350	30143
5(M80)	0.005700	34700	0.5000	90.20	0.01643	34935

J6.8 Stress & Strain Limits for Intermediate Strain Rate at High Temperature

J19a: Limits, Average, Intermediate Speed, High Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	42080	0.4300	319.5	0.02140	34150
2(H100)	0.01596	38620	0.4500	255.6	0.01555	35150
3(M100)	0.01030	53120	0.5500	242.3	0.01780	62090
4(M80)	0.01210	53280	0.6000	176.1	0.01350	60920
5(M80)	0.005700	34700	0.6000	176.1	0.01697	38520

J19b: Limits, High Bound, Intermediate Speed, High Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	45326	0.4500	329.1	0.02140	37065
2(H100)	0.01596	45739	0.4500	281.6	0.01555	36668
3(M100)	0.01030	65745	0.5500	257.1	0.01780	71333
4(M80)	0.01210	70795	0.6000	188.9	0.01350	91697
5(M80)	0.005700	34700	0.6000	188.9	0.01744	42105

J19c: Limits, Low Bound, Intermediate Speed, High Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	38834	0.4100	309.9	0.02140	31235
2(H100)	0.01305	31501	0.4500	229.6	0.01545	33632
3(M100)	0.01030	40495	0.5500	227.6	0.01780	52847
4(M80)	0.01210	35765	0.6000	163.4	0.01350	30143
5(M80)	0.005700	34700	0.6000	163.4	0.01643	34935

J6.9 Stress & Strain Limits for Slamming Strain Rate at High Temperature

J20a: Limits, Average, Slamming Speed, High Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	42080	0.4500	326.5	0.02140	34150
2(H100)	0.01596	38620	0.5000	267.2	0.01555	35150
3(M100)	0.01030	53120	0.5100	255.6	0.01780	62090
4(M80)	0.01210	53280	0.5000	190.3	0.01350	60920
5(M80)	0.005700	34700	0.5000	190.3	0.01697	38520

J20b: Limits, High Bound, Slamming Speed, High Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	45326	0.4500	336.6	0.02140	37065
2(H100)	0.01596	45739	0.5000	285.2	0.01555	36668
3(M100)	0.01030	65745	0.5100	265.1	0.01780	71333
4(M80)	0.01210	70795	0.5000	208.1	0.01350	91697
5(M80)	0.005700	34700	0.5000	208.1	0.01744	42105

J20c: Limits, Low Bound, Slamming Speed, High Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	38834	0.4500	316.4	0.02140	31235
2(H100)	0.01305	31501	0.5000	249.2	0.01545	33632
3(M100)	0.01030	40495	0.5100	246.1	0.01780	52847
4(M80)	0.01210	35765	0.5000	172.4	0.01350	30143
5(M80)	0.005700	34700	0.5000	172.4	0.01643	34935

J6.10 Stress & Strain Limits for Quasi-Static Strain Rate at Low Temperature

J21a: Limits, Average, Quasi-Static Speed, Low Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	42080	0.1800	331.2	0.02140	34150
2(H100)	0.01596	38620	0.1750	260.4	0.01555	35150
3(M100)	0.01030	53120	0.09500	248.4	0.01780	62090
4(M80)	0.01210	53280	0.2000	176.6	0.01350	60920
5(M80)	0.005700	34700	0.2000	176.6	0.01697	38520

J21b: Limits, High Bound, Quasi-Static Speed, Low Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	45326	0.1800	339.4	0.02140	37065
2(H100)	0.01596	45739	0.1750	282.5	0.01555	36668
3(M100)	0.01030	65745	0.09500	262.6	0.01780	71333
4(M80)	0.01210	70795	0.2000	195.0	0.01350	91697
5(M80)	0.005700	34700	0.2000	195.0	0.01744	42105

J21c: Limits, Low Bound, Quasi-Static Speed, Low Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	38834	0.1800	322.9	0.02140	31235
2(H100)	0.01305	31501	0.1750	238.3	0.01545	33632
3(M100)	0.01030	40495	0.09500	234.1	0.01780	52847
4(M80)	0.01210	35765	0.2000	158.3	0.01350	30143
5(M80)	0.005700	34700	0.2000	158.3	0.01643	34935

J6.11 Stress & Strain Limits for Intermediate Strain Rate at Low Temperature

J22a: Limits, Average, Intermediate Speed, Low Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	42080	0.1350	382.6	0.02140	34150
2(H100)	0.01596	38620	0.1250	303.1	0.01555	35150
3(M100)	0.01030	53120	0.09500	305.5	0.01780	62090
4(M80)	0.01210	53280	0.1750	213.1	0.01350	60920
5(M80)	0.005700	34700	0.1750	213.1	0.01697	38520

J22b: Limits, High Bound, Intermediate Speed, Low Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	45326	0.1350	392.5	0.02140	37065
2(H100)	0.01596	45739	0.1250	324.0	0.01555	36668
3(M100)	0.01030	65745	0.09500	316.2	0.01780	71333
4(M80)	0.01210	70795	0.1750	226.3	0.01350	91697
5(M80)	0.005700	34700	0.1750	226.3	0.01744	42105

J22c: Limits, Low Bound, Intermediate Speed, Low Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	38834	0.1350	372.7	0.02140	31235
2(H100)	0.01305	31501	0.1250	282.2	0.01545	33632
3(M100)	0.01030	40495	0.09500	294.9	0.01780	52847
4(M80)	0.01210	35765	0.1750	199.8	0.01350	30143
5(M80)	0.005700	34700	0.1750	199.8	0.01643	34935

J6.12 Stress & Strain Limits for Slamming Strain Rate at Low Temperature

J23a: Limits, Average, Slamming Speed, Low Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	42080	0.1250	411.1	0.02140	34150
2(H100)	0.01596	38620	0.1300	315.9	0.01555	35150
3(M100)	0.01030	53120	0.07500	340.8	0.01780	62090
4(M80)	0.01210	53280	0.06000	226.0	0.01350	60920
5(M80)	0.005700	34700	0.06000	226	0.01697	38520

J23b: Limits, High Bound, Slamming Speed, Low Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	45326	0.1250	425.2	0.02140	37065
2(H100)	0.01596	45739	0.1300	330.9	0.01555	36668
3(M100)	0.01030	65745	0.07500	350.5	0.01780	71333
4(M80)	0.01210	70795	0.06000	232.0	0.01350	91697
5(M80)	0.005700	34700	0.06000	232.0	0.01744	42105

J23c: Limits, Low Bound, Slamming Speed, Low Temperature

Panel	Top Skin		Core		Bottom Skin	
Type	$Strain_t$	$Stress_t$	$Strain_c$	$Stress_c$	$Strain_b$	$Stress_b$
1(H130)	0.01020	38834	0.1250	397.1	0.02140	31235
2(H100)	0.01305	31501	0.1300	301.0	0.01545	33632
3(M100)	0.01030	40495	0.07500	331.1	0.01780	52847
4(M80)	0.01210	35765	0.06000	219.9	0.01350	30143
5(M80)	0.005700	34700	0.06000	219.9	0.01643	34935