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FABRICATION OF CURVED GRAPHITE/EPOXY COMPRESSION TEST PANELS AND GENERATION OF MATERIAL PROPERTIES

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FOREWORD

The work in this program was performed under the direction of the Structural Concepts Evaluation Group, Structural Concepts Branch, Structures and Dynamics Division, Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories. Harold Croop served as project engineer. The work was performed under Work Unit 24010366, "Composite Assessment and Repair."

Special appreciation is given to Paul Rimer and particularly Debbie Oliveira of the Beta Industries operated Composites Facility, and Richard Rolfes, Quality Assurance Evaluator, for their considerable expertise in the manufacture and preparation of the test specimens and test panels.

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This report was typed by Corinne Burke, Survivability/Supportability Group, and Ray Hoskins, Structural Concepts Evaluation Group, both of the Structural Concepts Branch, using the new DECmate II word processing system. The text was then loaded to an Apple MacIntosh system by Forrest Sandow for final editing and output on a laser printer.

This technical memorandum has been reviewed and is approved for publication.

Larry G. Kelly
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SECTION I
INTRODUCTION

This project was undertaken at the request of Dr Anthony N Palazotto of the Air Force Institute of Technology (AFIT/ENY) and Capt Gary Seifert, a Master's degree student under Dr Palazotto, to investigate the effects on buckling behavior of centrally located delaminations in rectangular, curved, graphite/epoxy (AS4/3502) panels. This report documents the material properties data generation for this project and the fabrication of the curved test panels. The actual compression testing of the curved panels was performed under the cognizance of Capt Seifert. A summary of the entire program including the panel buckling tests is contained in Capt Seifert's Master's thesis: The Effect of Center Delamination on the Instability of Composite Cylindrical Panels, AFIT/GAE/AA/84D-25, Dec 84.

The reader will note that two sets of material properties values are reported. One set reflects excessive voidiness (greater than 1%) in the panels. A second set of panels was subsequently fabricated with an acceptable (less than 1%) level of voidiness. It was decided to report both sets of values as a measure of the effect of excessive porosity on the material properties, particularly matrix dominated properties.

Prior to fabricating the curved panels, a qualitative test was conducted to select a suitable material for simulating delaminations. C-Scan of two panels with various embedded delamination inducing materials was also conducted to assess the ability to properly position and subsequently locate the delaminations. Results of these assessments are reported herein.

SECTION II
MATERIAL PROPERTIES

1. Test Methods

a. 0 Deg Tensile

The 0 deg tensile tests were performed according to ASTM Standard D 3039. The specimens were machined from $[0]_{16}$ layups (Table 1, panels C08284-5 and C10184-2) and measured 10 in. by 0.5 in. Tabs measuring 2 in. long were secondarily bonded. Tab thicknesses, based upon available materials, were 0.062 in. for the voidy specimens and 0.10 in. for the non-voidy specimens. The specimens were strain-gaged at their midpoints on both sides with strains being recorded both parallel to and perpendicular to the fiber direction. Cross head speed was 0.05 in./min.

The ultimate tensile strength was calculated as follows:

$$\textbf{Ultimate tensile strength} = P/bt$$

where:

P = failure load

b = specimen width

t = specimen thickness

The tensile modulus in the fiber direction was calculated as follows:

$$\textbf{0 Deg Tensile Modulus} = \frac{\Delta P}{\Delta \varepsilon_L} \frac{1}{bt}$$

where:

$\Delta P/\Delta\varepsilon_L$ = slope of load vs specimen longitudinal strain within linear portion of curve

The Poisson's ratio was calculated using the following relation:

$$\textbf{Poisson's ratio} = -\Delta\varepsilon_T / \Delta\varepsilon_L$$

where:

$\Delta\varepsilon_T / \Delta\varepsilon_L$ = slope of transverse strain vs longitudinal strain within linear portion of curve

b. 90 Deg Tensile

The 90 deg tensile tests were also performed according to ASTM Standard D 3039. The specimens were again extracted from 16 ply unidirectional layups (Table 1, panels C08184-3 and C10184-1) and were cut to measure 7.5 in. perpendicular to the fiber by 1 in. parallel to the fiber. Tabs were not used. Specimens were strain-gaged on both sides at their midpoints. Cross head speed was 0.05 in./min. Ultimate tensile strength and Young's Modulus perpendicular to the fiber were calculated according to the relations given under 0 deg tensile.

c. ±45 Deg Tensile

Inplane unidirectional shear strength and shear modulus were evaluated according to ASTM Standard D 3518. The ±45 deg tensile specimens measured 11 in. by 1 in. Tabs measuring 2 in. in length were secondarily bonded. Tab thicknesses, based upon available materials, were 0.062 in. (1/16 in.) for the voidy specimens and 0.10 in (1/10 in.) for the non-voidy specimens. Two-element strain gages were bonded at the midpoints of both sides of each specimen. Cross head speed was 0.05 in./min. Three different layups were evaluated: $[\pm 45]_{2s}$, $[\pm 45]_{4s}$, and a non-standard $[(\pm 45)_{2s} / \overline{AF163}]_s$. According to D 3518, the specimen thickness may be anywhere from approximately 4 to 20 plies. The 8 ply layup (Table 1, panels C08284-3 and

C10184-5) was chosen since the test panels were to be 8 plies. The 16 ply layup (Table 1, panels C08284-4 and C10184-6) was chosen to evaluate shear property sensitivity to specimen thickness. The non-standard 16 ply bonded layup (Table 1, panels C08284-1/2 and C10184-3/4) was included for comparison with the other two similar layups. The 16 ply bonded layup was fabricated by secondarily bonding together two 8 ply layups.

The ultimate inplane unidirectional shear strength was calculated as follows:

Ultimate unidirectional shear strength = P/2bt

where:

P = failure load

b = specimen width

t = specimen thickness

The unidirectional shear modulus was calculated according to the following relations:

Unidirectional shear modulus = $\Delta\tau_{12}/\Delta\gamma_{12}$

where:

$\Delta\tau_{12}/\Delta\gamma_{12}$ = slope of unidirectional shear stress-strain curve within the linear portion of curve

$\Delta\tau_{12} = \Delta P/2bt$

ΔP = a delta load within linear portion of the ±45 deg tensile load vs strain curve

$\Delta\gamma_{12} = \Delta\varepsilon_L - \Delta\varepsilon_T$

$\Delta\varepsilon_L$ = the delta longitudinal strain within the specimen corresponding to the ΔP

$\Delta\varepsilon_T$ = the delta transverse strain within the specimen corresponding to the ΔP

d. 0 Deg Flexure

The 0 deg flexural specimens were tested according to ASTM Standard D 790. The specimens, machined from panels 16 plies in thickness (Table 1, panels C08284-5 and C10184-2), measured 4 in. by 1 in. A 3 in. support span was utilized which yielded a support span-to-depth ratio of about 35 to 40 depending upon specific specimen thickness. This is consistent with ASTM guidelines for a material having a ratio of tensile strength to shear strength greater than 8 to 1. Three-point loading was performed at a cross head speed of 0.05 in./min.

For three-point loading, the flexural strength or maximum fiber stress was calculated as follows:

$$\textbf{Flexural Strength} = \frac{3PL}{2bt^2}$$

where:

P = failure load

L = support span

b = specimen width

t = specimen thickness

The modulus of elasticity in bending was also calculated as follows:

$$\textbf{Modulus in bending} = \frac{L^3 m}{4b\, t^3}$$

where:

m = slope of initial straight-line portion of load-deflection curve

e. 90 Deg Flexure

The 90 deg flexural properties were also evaluated according to ASTM Standard D 790. Specimens were again extracted from 16 ply panels (Table 1, panels C08184-3 and C10184-1) and were cut to measure 2.5 in. by 1 in. Four-point loading was performed with the minor (load) span equaling 0.5 times the major (support) span of 1.5 in. The support span-to-depth ratio was about 19 to 20 depending upon the specific specimen thickness. Because of the fragility of 90 deg specimens, four-point loading was chosen to relocate the points of upper fixture load application away from the point of maximum deflection of the beam. This loading method creates a condition of zero shear and constant bending stress over the loading span. Cross head speed was 0.05 in./min.

For four-point loading, the flexural strength of the matrix was calculated as follows:

$$\textbf{Flexural strength} = \frac{3PL}{4bt^2}$$

where:

P = failure load

L = support span

b = specimen width

t = specimen thickness

The modulus of elasticity of the matrix in bending was determined by the following:

$$\textbf{Modulus in bending} = \frac{11}{64} L^3 \frac{m}{bt^3}$$

where:

m = slope of initial straight-line portion of load-deflection curve

f. Short Beam Shear

Short beam shear tests were performed according to ASTM Standard D 2344. The specimens were unidirectional 16 ply layups measuring 0.5 in. in the fiber direction by 0.25 in. wide. A support span of 0.33 in. was specified. This span was unavailable in the testing facility. A span of 0.36 in. was subsequently substituted. The support span-to-depth ratio was consequently about 4.6 for the voidy specimens (Table 1, panel C08284-5) and 4.9 for the non-voidy specimens (Table 1, panel C10184-2). The ASTM Standard recommends a ratio of 4 for elastic modulus greater than 14.5×10^6 psi and 5 for elastic modulus less than 14.5×10^6 psi. For this material, the desired support span-to-depth ratio was thus about 4. The specimens, nevertheless, did fail in a shearing type mode as desired (Section II.3). Cross head speed was 0.05 in./min.

The apparent interlaminar shear strength was calculated as follows:

$$\textbf{Shear Strength} = \frac{3\ P}{4\ bt}$$

where:

P = failure load

b = specimen width

t = specimen thickness

2. Specimen Fabrication

Six 12 in. by 18 in. panels of AS4/3502 graphite/epoxy were required to provide all of the material properties specimens. The cutout plan for these specimens is depicted in Figure 1 along with the stacking sequences and fiber directions. One-half in. peripheral trim was allotted for all panels. The initial set of six panels, however, was visibly voidy as verified by C-scan and subsequent constituent analysis by acid digestion (ref Table 1 panels C08284-1 through 5 and C08184-3).

The cure cycle used for these panels was as follows:

a. Apply full vacuum, 25 in. Hg minimum.

b. Heat air to 350F in 45 ± 5 min. using 90KW at 100%.

c. When part reaches 230F, cool air to 250F in 15 min. Part and air should reach 250F at about the same time.

d. Hold part at 250 ± 5F for 60 min. under full vacuum.

e. Heat air to 380F using 90KW at 100%.

f. Apply 85 psi using nitrogen when air temperature reaches about 365F during the heat-up of step e.

g. Cool air such that air and part reach 350F at about the same time. Vent vacuum.

h. Hold part at 350 ± 5F for 120 min. under 85 psi.

i. Cool part below 150F in 120 ± 5 min. maintaining pressure.

j. When part is below 150F, vent pressure.

The above procedure is a variation of the FIBC Composites Facility autoclave cycle designated B-250-T. In place of steps e, f, and g, B-250-T calls for the following:

e. Apply 85 psi using nitrogen.

f. Heat air to 350F in 20 ± 5 min. using 90KW at 100%.

g. When part reaches 350F, vent vacuum.

The variation in procedure was implemented due to the presence of other, more massive layups in the autoclave which were thought would have slower heat-up rates.

To retard the heat-up rates of the six material properties panels, the panels (along with 2 additional 12 in. by 18 in., 8 ply panels for evaluation of delamination materials as discussed in Sections III.1 and III.2) were stacked under a single vacuum bag. The stacking/bagging sequence was as follows:

a. Backing plate (dolly top)
b. Mylar
c. CHR (non-porous, Teflon coated glass cloth
d. Nylon peel ply
e. Laminate
f. Nylon peel ply
g. TX 1040 (porous, Teflon coated glass cloth)
h. Mochburg bleeder (l ea)
i. TX 1040
j. Caul plate
k. Repeat of "b" through "j" for each of the remaining 7 panels except 16 ply panels had an extra Mochburg
l. SSFR vent blanket
m. Vacuum bag

The edge dam was Coroprene. Only layer "i" for the top panel was sealed to the dam.

In addition to the 6 material properties panels, the 2 cured delamination evaluation panels were also visibly voidy, but were retained for their originally planned evaluation as discussed in Sections III.1 and III.2. With respect to the material properties panels,however, it was decided to not only manufacture a second set of panels but also to test a reduced number of specimens from the voidy panels to assess the degree of property degradation due to the excessive porosity. Five specimens of each type, instead of the originally planned ten, were tested, except for the ±45 deg tensiles in which case only two of each were tested. The latter accrued due to excessive warpage of all of the tensile shear specimens. This warpage was attributed to a nonapproved deviation from the standard Composites Facility techniques, in which bonding of the end tabs was by a vacuum bag over a panel assembly, but without support of the lower surface of the panel between the tabs.

While testing of the above specimens proceeded, the second set of six panels was fabricated. The cure cycle used for these panels was also procedure B-250-T. These panels were stacked and bagged according to the order given for the first set of panels. The second set of panels exhibited acceptable levels of porosity (ref Table 1 panels C10184-1 through 6), leading one to conclude that the variation in cure cycle caused the excessive porosity in the first set of panels. The high autoclave temperatures, long heat times (at low pressure), and delayed pressure application probably caused gel onset before full application of pressure. Ten specimens of each type from the second set of panels were subsequently tested with the exception of the bonded tensile shear specimens. These specimens were produced by bond-laminating panels C10184-3 and 4 using AF-163 250F cure epoxy adhesive. These were warped in the same manner as the voidy, tensile shear specimens. Cause of warpage was again attributed to the aforementioned nonapproved procedure of tab application.

The final two panels, C13784-2 and 3, were subsequently fabricated to provide the remaining needed tensile shear specimens. The cure cycle employed for the final two panels carries the FIBC Composites Facility designation B-270. This cycle calls for the following steps:

a. Apply full vacuum, 25 in. Hg minimum.

b. Heat air to 350F in 45 ± 5 min. using 90KW at 100%.

c. When part reaches 250F, cool air to 270F in 10-15 min. Part should reach 270F at same time as air.

d. Hold part at 270 ± 5F for 15 min. under full vacuum.

e. Apply 85 psi using nitrogen.

f. Hold part at 270 ± 5F at 85 psi and under full vacuum for 45 min.

g. Heat air to 350F as rapidly as possible using 90KW at 100%.

h. When part reaches 350 ± 5F, hold at temperature at 85 psi and under full vacuum for 15 min. Vent vacuum.

i. Hold part at 350 ± 5F and 85 psi for 105 min.

j. Cool part below 150F in 60 ± 5 min. maintaining 85 psi.

k. When part is below 150F, vent pressure.

Cycle B-270 was employed for the final two panels instead of the earlier B-250-T after the government became aware of the arbitrary and independently determined cycle previously employed by the facility contractor. Cycle B-270 was based on a 270 F dwell, comparable to major usage in the industry for the AS4/3502 material. These panels were stacked and bagged in the manner indicated for the first two sets of panels. The final two panels were also found to possess acceptable levels of porosity, and the bonded specimens derived from them exhibited no warpage. It should be noted as indicated in Table 1 that this cure cycle yielded constituent analyses results very similar to those from the second set of six panels.

Quality assurance was assured by C-Scan of the panels prior to specimen cutting as well as the previously cited constituent analyses. These analyses were performed on three samples from each panel. The specimens were dimensionally characterized according to the requirements of Figure 2. Prior to and during the test, the specimens were exposed to ambient conditions of temperature and humidity. Exposure averaged several weeks to several months from time of panel cure to specimen testing. All specimens were cut using a diamond bladed circular saw.

3. Results

Results of the material properties testing are summarized in Table 2 for both the voidy and non-voidy specimens. The properties calculated for the double gaged specimes represent averages of the two values of a given property as determined by each of the strain gage outputs. Matrix dominated properties for the voidy specimens are consistently lower than those for the non-voidy specimens, as one would expect. Individual test values are presented in Tables 3 through 10.

Zero deg tensile specimens exhibited typical splintering types of failures. The 90 deg tensile specimens failed cleanly across their widths but with a predominance of failures, about 50%, occurring approximately at the endpoint of a grip. The ±45 deg tensile specimens failed along the ±45 deg axes. These failures occurred almost uniformly at the transition of an end tab into the specimen. Normally this test is not carried to failure since only modulus data is obtained from the test. Table 11 provides a listing of the failure locations and crosshead displacements for the three different types of tensile shear specimens. The 16 ply specimens on average exhibited greater displacement to failure than either the 8 ply or the 16 ply bonded specimens. The 8 ply and 16 ply bonded specimens exhibited similar displacements to failure on average. As indicated in Table 2, the average ultimate shear strength of the 8 ply specimens was the same as that of the 16 ply bonded specimens, with that of the 16 ply specimens being about 10% greater. In terms of shear modulus, the 16 ply and 16 ply bonded specimens were nearly identical whereas the 8 ply specimens exhibited about 7% less shear stiffness. One can thus conclude that sensitivity of shear properties to specimen thickness was indicated. Also, the 16 ply bonded specimens did not consistently mimic the behavior of either the 8 ply or 16 ply specimens. The 0 deg flexure specimens failed at their midpoints, the point of upper fixture load application, exhibiting fiber tensile breakage fairly uniformly across their widths. The 90 deg flexure specimens cracked generally at or near one of the minor span load introduction points. The short beam shear specimens failed via either single or multiple cracking occurring interlaminarly.

SECTION III
CURVED PANELS

1. Selection of Delamination Material

Since the curved panels were to contain simulated delaminations, it was first necessary to select a suitable material which would create a delamination. A single 12 in. by 18 in. panel of AS4/3502 graphite/epoxy having orientation $[0/90]_{2s}$ was layed up and cured with samples of six different materials embedded between plies 4 and 5 (Figure 3). The six materials chosen were 1 mil mylar, 1 mil mylar with RAM 225 release agent applied to both sides, backing paper (from AS4/3502 prepreg) with and without RAM 225, 3 mil non-porous Teflon, and nylon peel ply with RAM 225 applied to both sides. These materials were chosen based on ready availability to the Composites Facility. The stacking sequence represented one of two required ply orientations for the curved panels. To evaluate effectiveness of the materials, the panel was trimmed along its length on both sides such that the cuts passed through all six material samples. A simple visual examination of the cut edges revealed gaping delaminations for the following materials: 1 mil mylar, 1 mil mylar with release, and non-porous Teflon. The backing paper exhibited a slight cracking. Nylon peel ply showed no delamination as also did backing paper with release. Small rectangular samples about 1 in. by 1 in. were then cut from within the area of each candidate delamination material. Five of the samples readily separated or fell apart. These were the mylar with and without release, non-porous teflon, and backing paper with and without release. Only the nylon peel ply sample resisted easy separation under finger pressure. Based on the above, mylar with and without RAM 225 release and nonporous Teflon were all unequivocally acceptable as delaminating materials. Since it was desired that the thickness increase due to the delamination material be held to a minimum, the 1 mil mylar was selected. Application of RAM 225 release agent was also specified to provide added insurance of delamination.

2. Verification of Delamination Location

The panel of paragraph 1 was C-Scanned prior to trimming to verify ability to locate the delaminations and to check for insert migration. Results of the C-Scan are shown in Figure 4. All delaminations were clearly visible and corresponded to the initial positionings of the insert materials. A second 12 in. by 18 in. panel of AS4/3502, but of orientation $[0/\mp 45/90]_s$, having an identical set of delaminating materials embedded between plies 4 and 5, was also fabricated and C-Scanned. The panel configuration and C-Scan are depicted in Figures 5 and 6 respectively. These delaminations, of circular area, were also clearly discernible and showed no migration. The circular shape was chosen since the curved test panels were to have circular delaminations as a circular shape would not be subject to rotational inaccuracy. The two different ply orientations corresponded to the ply orientation requirements for the curved panels. This simple evaluation demonstrated there would be no difficulty in properly positioning and subsequently locating the delaminations, regardless of which defect material was used, or the stacking sequence of the laminate.

3. Fabrication of Curved Panels

A total of twenty-four curved graphite/epoxy (AS4/3502) test panels with and without delaminations was required. All panels were of 13 in. length, but of two different arc lengths-8.5 in. and 12.5 in. The tool available for fabricating the panels is shown in Figure 7. As indicated, the tool yields panels having a 12 in. radius as measured to the outer, convex surface of the panel. It was determined that the surface area of the tool was large enough that four test panels could be extracted from the lay up and cure of a single larger panel. The dimensions of a large panel are given in Figure 8. Since four tools were available, it was decided to conduct two autoclave runs utilizing the four tools each time, thereby yielding a total of thirty-two test panels. This resulted in eight extra panels which would be available if needed. A summary of the eight large panels is given in Table 12. A listing of the thirty-two individual test panels is given in Table 13. It is noted that the curved test panels contained either a 2 in. diameter defect, a 4 in. diameter defect, or no defect. Results of the constituent analyses (by acid digestion) of the eight large panels are given in Table 14. The eight large curved panels were cured according to two cure cycles. Panels dash 1 through dash 4 as listed in Table 12 were cured according to B-250-T. The remainder were cured according to B-270. As explained under Section II.2, "Specimen Fabrication," the cure cycle was changed to B-270 after the government facility manager became aware that a nonstandard cycle was being used by the facility contractor for AS4/3502 material. From the constituent analyses of Table 12 and C-Scan results, both cycles produced reasonably void free panels although the B-270 cured panels were consistently lower in void content than the B-250-T cured panels. The bagging sequence for each of the 8 large curved panels was as follows:

a. Curved tool
b. Mylar
c. CHR (non-porous, Teflon coated glass cloth)
d. Nylon peel ply
e. Laminate
f. Nylon peel ply
g. TX 1040 (porous, Teflon coated glass cloth)
h. Mochburg bleeder
i. Perforated mylar (sealed to a Coroprene edge dam)

j. Caul plate

k. SSFR vent blanket

l. Vacuum bag

It should be noted that a mylar template was used to properly position the delamination causing materials in each of the large curved panels. In addition to C-Scan, a hand held ultrasonic device was employed to more precisely mark the delamination locations in order that the individual test panels could be accurately cut from the large panels. The cutting was accomplished on a Bridgeport mill equipped with a diamond bladed circular saw. After cutting and as discussed in Capt Seifert's Master's thesis, length variation was determined for all 24 panels selected for test. An accept/reject criteria of 0.01 in. for the 12 in. arc length panels and 0.007 in. for the 8 in. arc length panels was established by Capt Seifert. Of the 24 panels, 7 failed to meet this criteria. These 7 panels were subsequently tested by Capt Seifert along with the good panels to reconfirm the accept/reject criteria. The criteria was reportedly found to be valid based upon the experimental output. None of the 8 extra panels was considered for test since Capt Seifert decided to restrict the experimental procedure to only the 24 panels. A discussion of the above along with the analytical predictions of buckling behavior and experimental results is fully contained in Capt Seifert's Master's thesis (Section I, Introduction).

SECTION IV
CONCLUSIONS

1. Material properties data was obtained for AS4/3502 graphite/epoxy, 12 in. wide unidirectional tape.

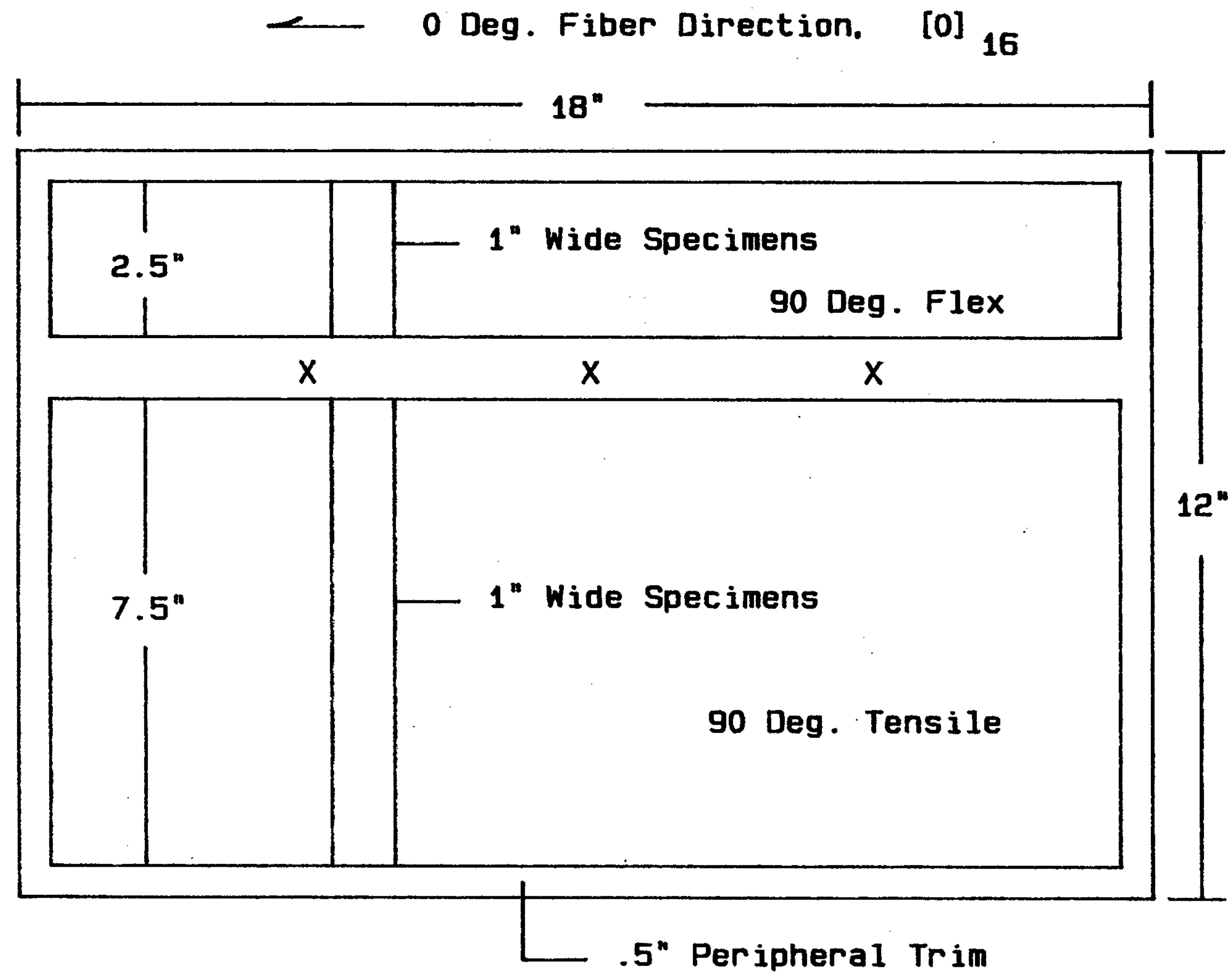
2. Some sensitivity of shear properties to specimen thickness was indicated, with the 16 ply specimens exhibiting slightly higher properties than the 8 ply specimens. A literature survey and additional testing, if necessary, are required, however, to fully investigate such a trend.

3. Since approximately 50% of the 90 deg tensile specimens failed at a grip, future tests should consider using sandpaper or similar frictional material under the grips as a stress reliever. Tabs are not recommended since the tabbing procedure itself may fracture the inherently fragile specimens.

4. One mil mylar with RAM 225 release agent applied to both sides effectively induces delamination in graphite/epoxy, with minimal additional thickness due to the included material.

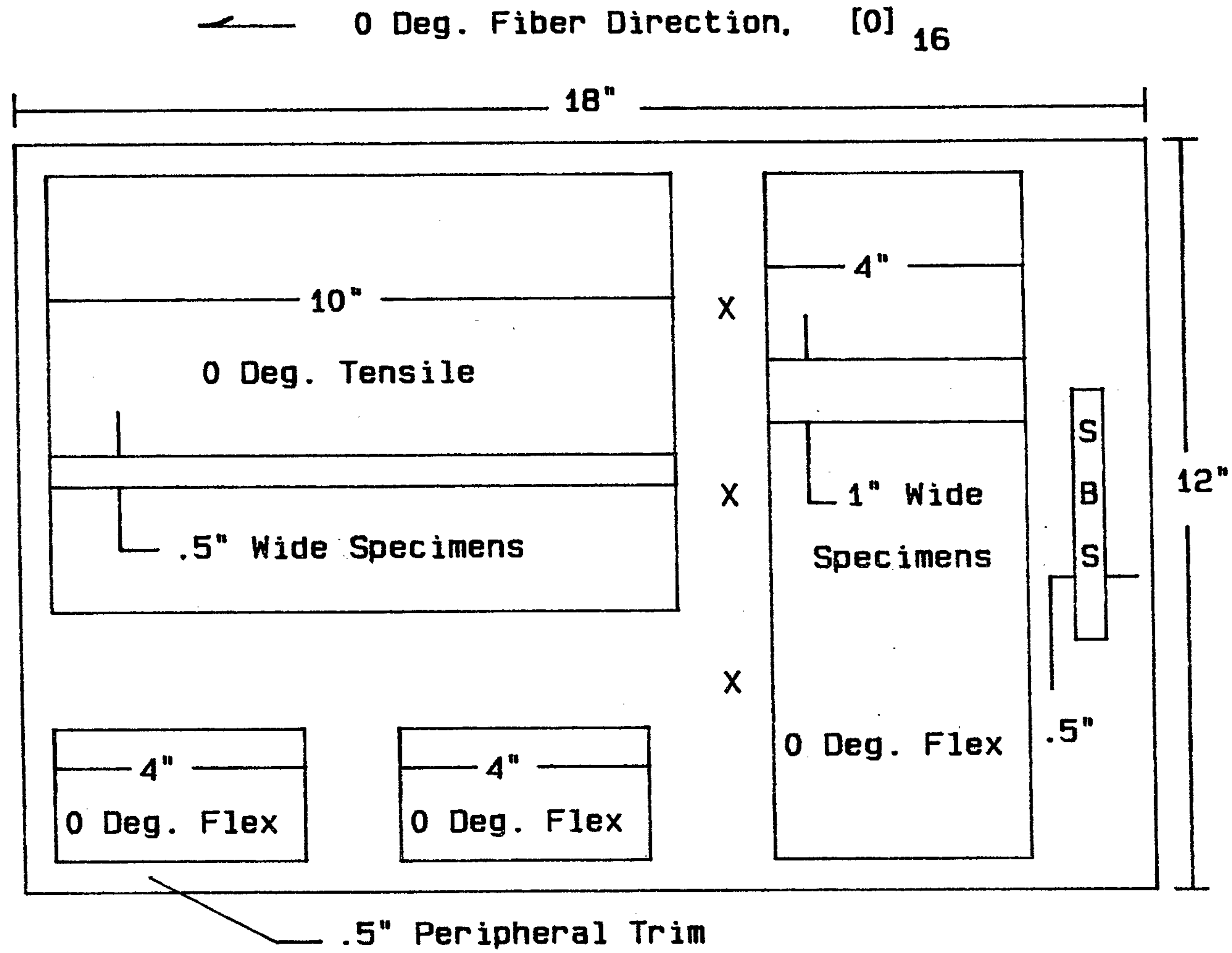
5. Curved graphite/epoxy panels with centrally located delaminations were successfully fabricated using available steel tooling.

6. Due to the high percentage of test panels having excessively out-of-parallel ends, consideration should be given in future fabrications of this kind to grinding the ends to achieve greater control over parallelism. The Bridgeport milling machine did not provide the consistent high degree of accuracy desired.



Note: X Denotes Constituent Analysis Specimen

Figure 1. Specimen Layout



Note: X Denotes Constituent Analysis Specimen

Figure 1 (Cont.) Specimen Layout

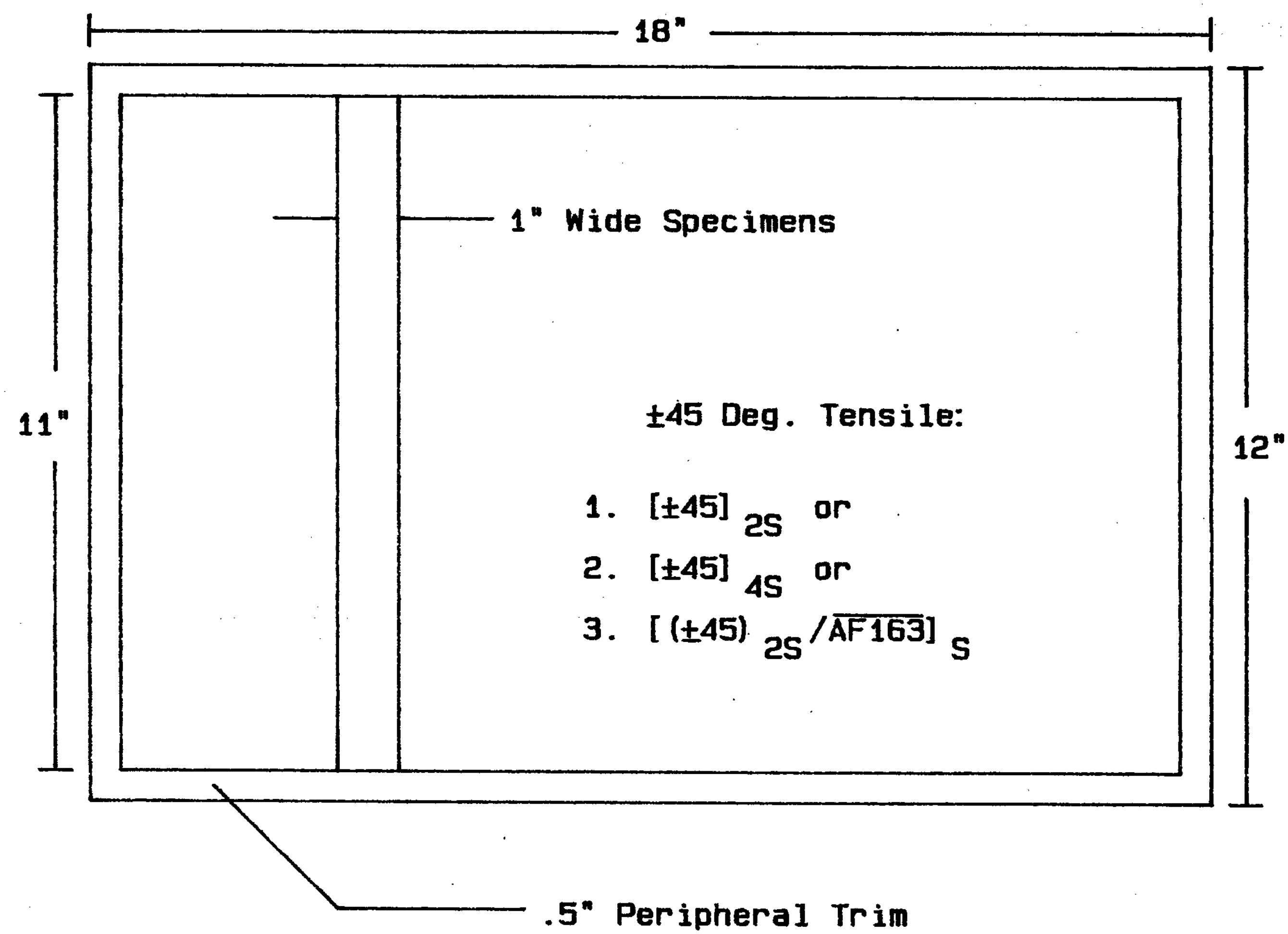
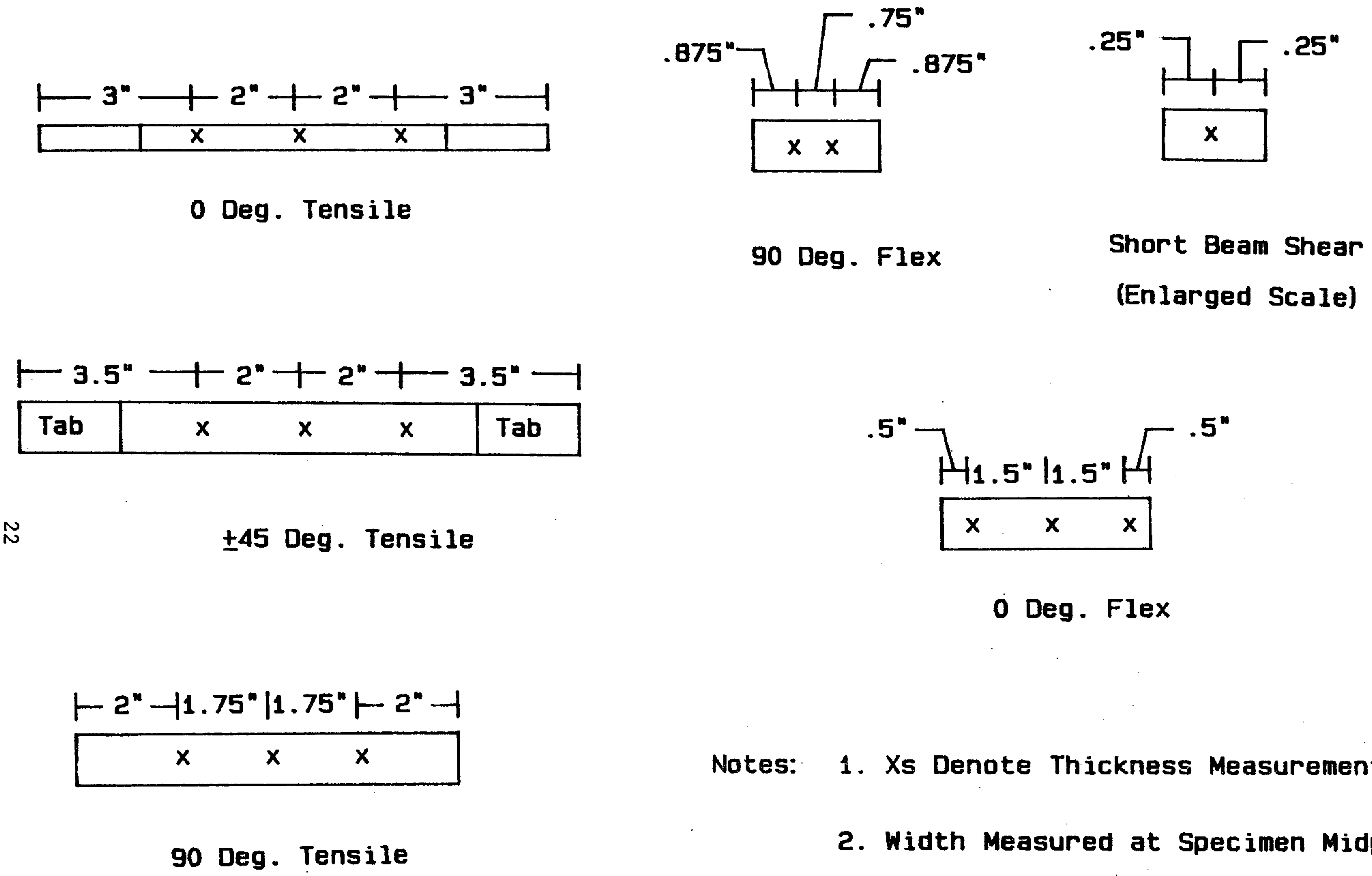


Figure 1 (Cont.). Specimen Layout



Notes: 1. Xs Denote Thickness Measurements

2. Width Measured at Specimen Midpoint

Figure 2. Specimen Dimensional Checks

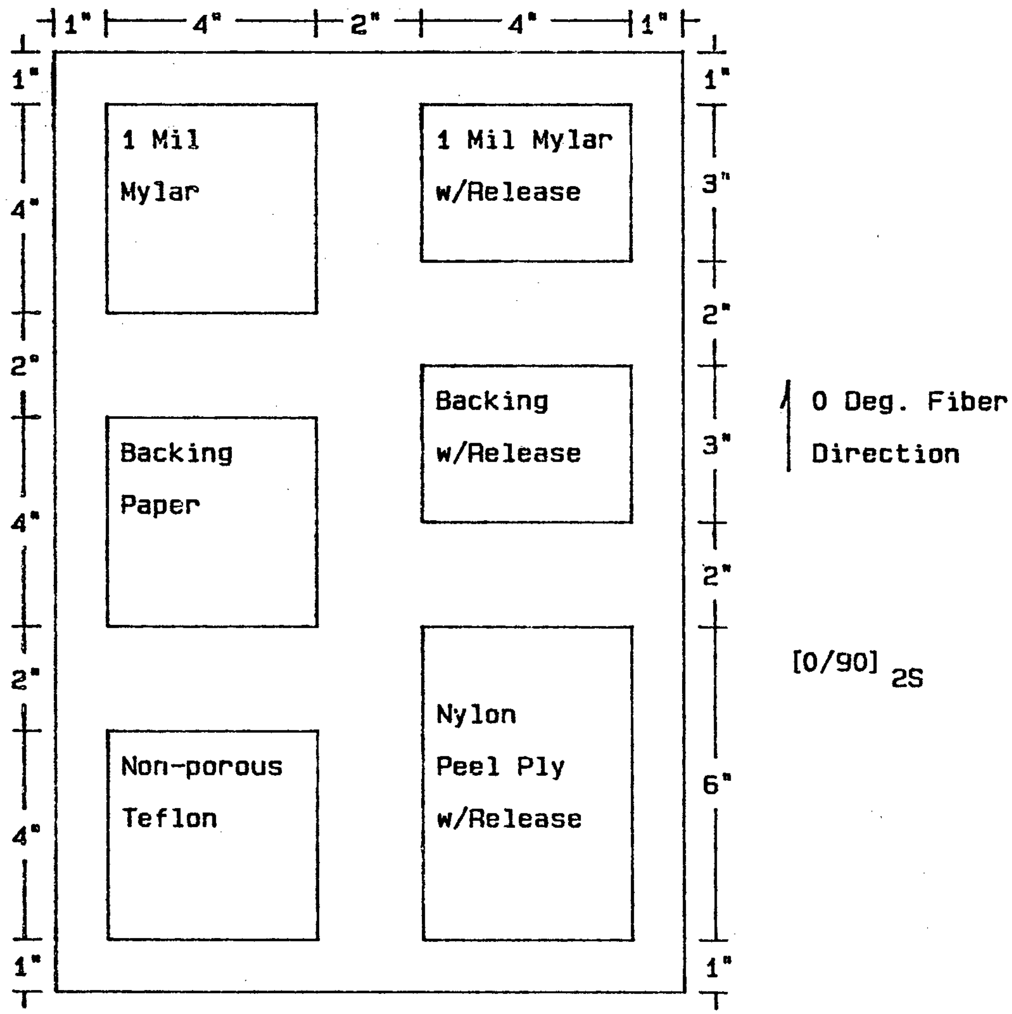
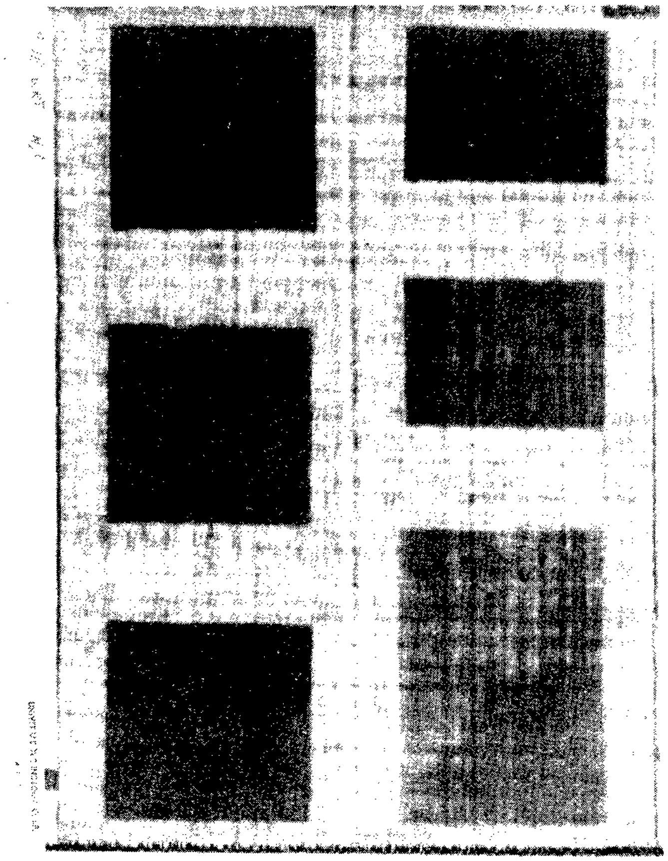
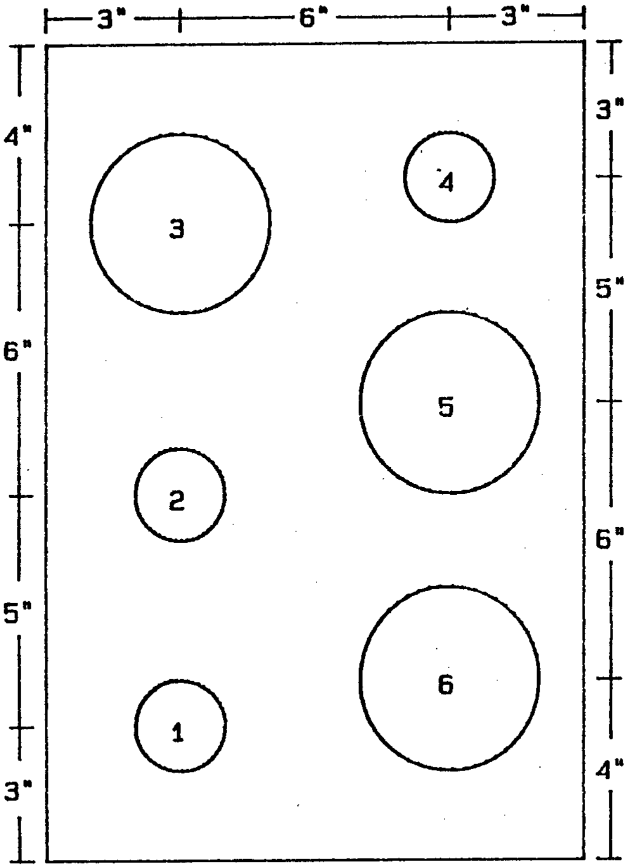


Figure 3. Rectangular Delamination Evaluation Panel



8 db wrt H_2O

Figure 4. C-Scan of Rectangular Delamination Evaluation Panel



Delamination Materials:

1 - 3 Mil Non-porous Teflon

2 - Backing Paper

3 - 1 Mil Mylar

4 - 1 Mil Mylar w/Release

5 - Backing w/ Release

6 - Nylon Peel Ply w/Release

$[0/-45/+45/90]_s$

0 Deg. Fiber Direction

Figure 5. Circular Delamination Evaluation Panel

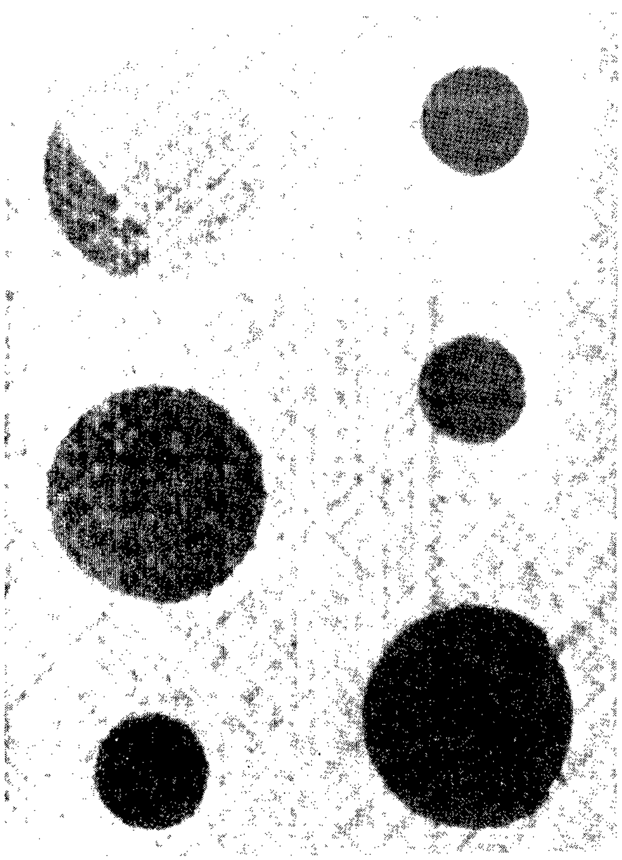


Figure 6. C-Scan of Circular Delamination Evaluation Panel

8 db wrt H_2O

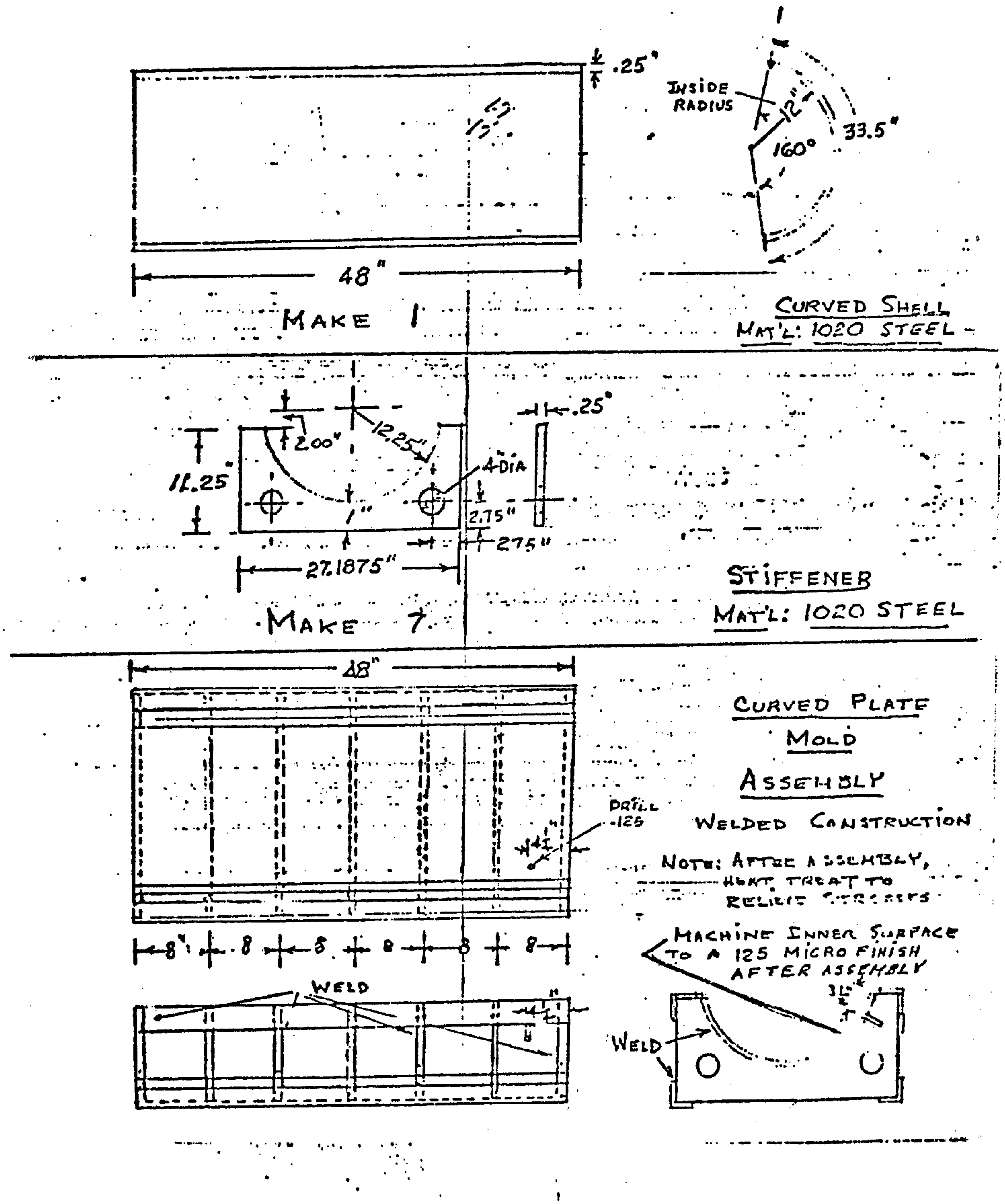


Figure 7. Tool Schematic

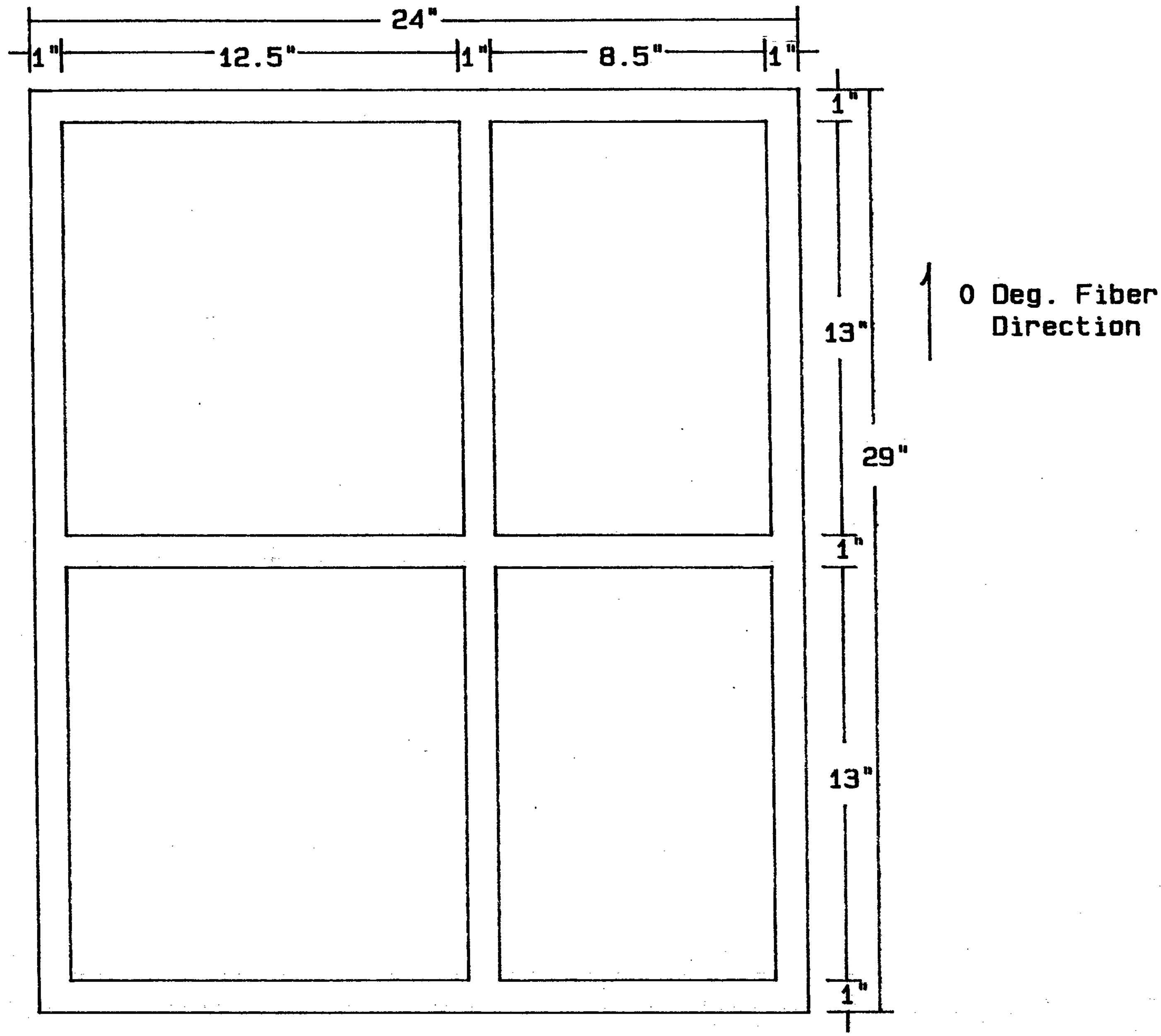


Figure 8. Large Curved Panel Layout

TABLE 1

CONSTITUENT ANALYSES - MATERIAL PROPERTIES PANELS

Panel	Specific Density	Resin Content Weight %	Void Content Volume %	Thickness (In.)	Thickness per Ply (In.)
C08284-1	1.57	28.5	2.70	.042	.0052
C08284-2	1.56	28.0	3.40	.041	.0052
C08284-3	1.55	29.4	3.26	.039	.0049
C08284-4	1.56	28.6	3.36	.077	.0048
C08284-5	1.58	26.1	2.92	.079	.0049
C08184-3	1.60	24.6	2.32	.077	.0048
C10184-1	1.63	25.0	.17	.077	.0048
C10184-2	1.63	25.0	.02	.074	.0047
C10184-3	1.61	27.1	.62	.040	.0050
C10184-4	1.60	27.3	.68	.040	.0050
C10184-5	1.60	28.6	.32	.039	.0048
C10184-6	1.62	26.4	.31	.077	.0048
C13784-2	1.62	25.8	.36	.039	.0049
C13784-3	1.62	26.5	.24	.039	.0048

Note: All values represent averages of 3 samples

TABLE 2

SUMMARY OF MATERIAL PROPERTIES

Property	Non-Voidy	Voidy
0 Deg. Young's Modulus	21.0 MSI	20.8 MSI
0 Deg. Flexural Modulus	17.6 MSI	15.5 MSI
90 Deg. Young's modulus	1.53 MSI	1.41 MSI
90 Deg. Flexural Modulus	1.95 MSI	1.48 MSI
Shear Modulus		
8 Ply	.79 MSI	----
16 Ply	.84 MSI	----
16 Ply Bonded	.86 MSI	----
0 Deg. Ultimate Tensile Strength	284 KSI	284 KSI
0 Deg. Ultimate Flexural Strength	289 KSI	228 KSI
90 Deg. Ultimate Tensile Strength	6.7 KSI	3.5 KSI
90 Deg. Ultimate Flexural Strength	11.4 KSI	4.8 KSI
Ultimate Shear Strength		
8 Ply	10.5 KSI	----
16 Ply	11.4 KSI	----
16 Ply Bonded	10.5 KSI	----
Short Beam Shear Strength	17.1 KSI	11.1 KSI
Poisson's Ratio	.30	.29

TABLE 3

0 DEGREE TENSION

Young's Modulus (MSI) Non-Voidy	Young's Modulus (MSI) Voidy	Poisson's Ratio Non-Voidy	Poisson's Ratio Voidy	Ultimate Tensile Strength (KSI) Non-Voidy	Ultimate Tensile Strength (KSI) Voidy	
20.6	19.9	.29	.30	274	261	
20.5	22.8	.30	.30	277	296	
20.8	21.4	.30	.28	270	290	
22.7	19.5	.27	.29	302	292	
20.7	20.5	.31	.28	290	283	
22.6	----	.32	---	303	---	
20.8	----	.29	---	285	---	
20.5	----	.31	---	292	---	
20.4	----	.28	---	284	---	
20.1	----	.30	---	264	---	
21.0	20.8	.30	.29	284	284	Mean
.9	1.3	.01	.01	13	14	Std. Dev.
4.3%	6.3%	5.0%	3.4%	4.6%	4.9%	Coef. Var.

TABLE 4

90 DEGREE TENSION

Young's Modulus (MSI) Non-Voidy	Young's Modulus (MSI) Voidy	Ultimate Tensile Strength (KSI) Non-Voidy	Ultimate Tensile Strength (KSI) Voidy	
1.51	.14*	3.1	.3*	
1.44	1.38	8.1	3.7	
1.48	1.44	8.2	3.8	*=Censored
1.51	1.41	7.8	3.3	from
1.50	1.41	9.6	3.3	calculations
1.49	----	6.3	---	
1.62	----	7.6	---	
1.54	----	6.5	---	
1.47	----	3.3	---	
1.71	----	6.6	---	
1.53	1.41	6.7	3.5	Mean
.08	.02	2.1	.3	Std.Dev.
5.3%	1.7%	31.1%	7.5%	Coef. of Var.

TABLE 5

45 DEGREE TENSION (8 PLY)

Shear Modulus (MSI) Non-Voidy	Shear Modulus (MSI) Voidy	Ultimate Shear Strength (KSI) Non-Voidy		Ultimate Shear Strength (KSI) Voidy	
.86	.74	10.4	*	9.6	
.79	.81	11.0	1.5"+	9.8	
.78	---	10.8	*	---	*=Failure at tab
.84	---	10.6	*	---	
.78	---	10.4	*	---	
.70	---	10.1	2.0"+	---	+=Average distance of failure from tab
.70	---	10.3	1.3"+	---	
.85	---	10.6	*	---	
.78	---	10.5	1.0"+	---	
.77	---	10.5	*	---	
.79	---	10.5		---	Mean
.06	---	.3		---	Std. Dev.
7.1%	---	2.4%		---	Coef. of Var.

TABLE 6

45 DEGREE TENSION (16 PLY)

Shear Modulus (MSI) Non-Voidy	Shear Modulus (MSI) Voidy	Ultimate Shear Strength (KSI) Non-Voidy		Ultimate Shear Strength (KSI) Voidy	
.91	.65	11.1	*	11.0	
.94	.73	11.4	*	11.2	*=Failure at tab
.79	---	11.2	*	----	
.80	---	11.6	*	----	
.82	---	11.4	2.75"+	----	+=Average distance of failure from tab
.81	---	11.3	*	----	
.77	---	11.4	*	----	
.90	---	11.5	*	----	
.81	---	11.4	*	----	
---	---	----		----	
.84	---	11.4		----	Mean
.06	---	.2		----	Std. Dev.
7.3%	---	1.3%		----	Coef. of Var.

TABLE 7

45 DEGREE TENSION (16 PLY BONDED)

Shear Modulus (MSI) Non-Voidy	Shear Modulus (MSI) Voidy	Ultimate Shear Strength (KSI) Non-Voidy		Ultimate Shear Strength (KSI) Voidy	
.87	.65	10.9	*	9.5	*=Failure at tab
.93	.69	10.5	*	9.2	
.82	---	10.4	*	---	
.84	---	10.5	*	---	+=Average distance of failure from tab
.69	---	10.3	*	---	
.96	---	10.5	.5"	---	
.85	---	10.5	*	---	
.93	---	10.4	*	---	
.81	---	10.4	*	---	
.85	---	10.8	*	---	
.86	---	10.5		---	Mean
.08	---	.2		---	Std. Dev.
9.0%	---	1.8%		---	Coef. of Var.

TABLE 8

0 DEGREE FLEXURE

Flexural Modulus (MSI) Non-Voidy	Flexural Modulus (MSI) Voidy	Ultimate Flexural Strength (KSI) Non-Voidy	Ultimate Flexural Strength (KSI) Voidy	
18.2	15.7	327	237	
17.7	14.9	262	196	
17.5	15.9	264	217	
16.4	15.5	252	241	
16.5	15.3	238	251	
15.7	----	251	---	
19.4	----	313	---	
19.4	----	337	---	
18.4	----	331	---	
16.6	----	319	---	
17.6	15.5	289	228	Mean
1.3	.4	39	22	Std. Dev.
7.3%	2.5%	13.5%	9.6%	Coef. of Var.

TABLE 9

90 DEGREE FLEXURE

Flexural Modulus (MSI) Non-Voidy	Flexural Modulus (MSI) Voidy	Ultimate Flexural Strength (KSI) Non-Voidy	Ultimate Flexural Strength (KSI) Voidy	
2.04	----	16.1	4.8	
2.14	----	13.7	5.0	
1.86	1.61	8.4	5.7	
2.12	1.58	17.6	5.8	
1.90	1.26	6.7	2.8	
1.90	----	9.6	---	
1.91	----	9.6	---	
2.00	----	11.6	---	
1.71	----	10.0	---	
1.90	----	10.2	---	
1.95	1.48	11.4	4.8	Mean
.13	.19	3.4	1.2	Std. Dev.
6.6%	13.1%	30.4%	25.0%	Coef. of Var.

TABLE 10

SHORT BEAM SHEAR

Shear Strength (KSI) Non-Voidy	Voidy	
17.2	10.4	
17.3	9.8	
18.6	12.9	
16.1	11.3	
15.0	10.2	
16.9	12.3	
18.1	11.0	
18.7	12.0	
17.0	11.7	
16.0	9.6	
17.1	11.1	Mean
1.2	1.1	Std. Dev.
6.9%	10.0%	Coef. of Var.

TABLE 11

COMPARISON OF TENSILE SHEAR SPECIMEN FAILURES

8 Ply Specimens		16 Ply Specimens		16 Ply Bonded	
Crosshead Displacement (In.)	Failure Location	Crosshead Displacement (In.)	Failure Location	Crosshead Displacement (In.)	Failure Location
.49	Tab*	.26	Tab	.53	Tab
.47	1.5 in.**	.64	Tab	.32	Tab
.27	Tab	.65	Tab	.38	Tab
.59	Tab	-	Tab	.40	Tab
.63	Tab	.61	2.8 in.	.25	Tab
.21	2 in.	.60	Tab	.65	5 in.
.22	1.3 in.	.78	Tab	.65	Tab
.56	Tab	.74	Tab	.60	Tab
.62	1 in.	.77	Tab	.27	Tab
.63	Tab	.62	Tab	.26	Tab
.47		.63		.43	Mean
.17		.16		.16	Std. Dev.

* Tab means failure in the specimen at the beginning of a tab
** Average failure location as measured from the closest tab

Note: Non-voidy specimens

TABLE 12

LARGE CURVED PANEL FABRICATION SUMMARY

Panel #	Ply Orientation	Delamination
1	[0/-45/+45/90]s	2" dia.
2	"	4" dia.
3	"	None
4	"	8.5" subpanels(2) - 2" dia. in the one - 4" dia. in the other 12.5" subpanels(2) - same as above
5	[0/90/0/90]s	2" dia.
6	"	4" dia.
7	"	None
8	"	Same as panel 4

TABLE 13

TEST PANEL SUMMARY

Dimensions	Ply Orientation	Delamination	Number of Test Panels
8.5"x13"	[0/-45/+45/90]s	2" dia.	3
"	"	4" dia.	3
"	"	None	2
"	[0/90/0/90]s	2" dia.	3
"	"	4" dia.	3
"	"	None	2
12.5"x13"	[0/-45/+45/90]s	2" dia.	3
"	"	4" dia.	3
"	"	None	2
"	[0/90/0/90]s	2" dia.	3
"	"	4" dia.	3
"	"	None	2

TABLE 14

CONSTITUENT ANALYSES - LARGE CURVED PANELS

Panel	Specific Density	Resin Content Weight %	Void Content Volume %	Thickness (In.)	Thickness per Ply (In.)
C12184-1	1.61	26.0	.62	.040	.0050
C12184-2	1.61	26.3	.64	.039	.0048
C12284-3	1.61	26.4	.87	.039	.0048
C12282-4	1.60	26.3	1.20	.039	.0048
C12984-7	1.62	26.5	.29	.042	.0053
C12984-8	1.62	25.7	.14	.041	.0052
C13784-5	1.62	26.0	.19	.041	.0051
C13684-6	1.62	25.5	.41	.041	.0051

Note: All values represent averages of 3 samples

P0341

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