CNST MANTECH REPORT

SMART MANUFACTURING METHODS FOR CARBON / VINYL ESTER STRUCTURES

Title: Phase 1 – Final Report

Document – NGSB-5693-007

Revision – -

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Initial Issue Date: 10/07/08

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **07 OCT 2008**	2. REPORT TYPE	3. DATES COVERED **00-00-2008 to 00-00-2008**
4. TITLE AND SUBTITLE **Smart Manufacturing Methods for Carbon/Vinyl Ester Structures**		5a. CONTRACT NUMBER 5b. GRANT NUMBER 5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER 5e. TASK NUMBER 5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **CNST,5300 International Boulevard,Charleston,SC,29418**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S) 11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**17**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

AMT-KC1107-8027

To: Neil Graf (ONR), Office of Naval Research, Code 03T Manufacturing Technology, One Liberty Center, 875 North Randolph Street, Suite 1425, Arlington, VA 22203-1995

From: Kevin Carpentier, Director, Center for Naval Shipbuilding Technology

Date: 7 November 2008

Reference: (a) Contract No. N00014-03-C-0413 (CDRL Data Item No. A002)

Subject: Technical Project Report

In accordance with reference (a), the Smart Manufacturing Methods for Carbon/Vinyl Ester Structures Technical Report is attached. If you have any questions, please don't hesitate to contact me at (843)760-4364.

Attachment

Cc: Michael Karp (w/o attachment), ONR Administrative Contracting Officer
Defense Technical Information Center
Director, Naval Research Lab
DRC

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1. PROJECT SUMMARY

1.1 ABSTRACT

The US Navy is aggressively pursuing larger components constructed using fiber-reinforced plastic, or composite, materials. However, the overall processes involved in manufacturing high-strength, low weight composite components are still relatively new to US Navy shipbuilders. Vacuum Assisted Resin Transfer Molding (VARTM), a common composite fabrication methodology for composite structures, is extremely sensitive to the material systems used and the production set-up, or design. Any infusion-related defects easily lead to significant rework costs and schedule interruptions.

Focusing on the DDG 1000 composite deckhouse and hangar, the objective of this project was to develop a resin infusion process for each of two carbon fiber/vinyl ester resin composite joints that is predictable, repeatable, and reduces the defect rate experienced with current processes. Two common types of DDG 1000 composite deckhouse joints were examined in this project. Computer software was used to model and analyze the proposed VARTM infusion process designs, yielding optimized composite panel joint infusion processes. Resin flow sensors were installed in each joint, and were used to monitor resin flow fronts for the VARTM infusions. Non-Destructive evaluation of test specimens was performed to identify any potential defects in the test articles produced, and also validate the computer models.

- Sponsor
  - Neil Graf – ONR-ManTech
- Center for Naval Shipbuilding Technology
  - Program management; project oversight – Mr. Ivan Snell, CMTC
- PEO SHIPS – PMS 500 (DDG 1000) - NSWCCD
  - Stakeholder; technical authority assistance
- Northrop Grumman Shipbuilding, Gulf Coast
  - Project lead; requirements definition, implementation plan, technical and production preferences
- Subcontractors
  - University of Delaware, Center for Composite Materials (UD-CCM); SMARTMolding System, LIMS Software, and Modeling and Simulation services
  - Temeku Technologies; Technical Support

Figure 1 – Project Team

Based on successful infusion activities for simple and complex 2-D joint designs, it was determined that computer modeling is a useful tool in defining infusion set-ups for composite laminates with moderate (<1.25") cross-sectional thicknesses. An optimized infusion set-up resulted in simple 2-D joint specimens which successfully passed ultrasonic inspection, meeting DDG 1000 critical flaw size inspection criteria with no defects. The complex 2-D joint specimens successfully passed ultrasonic inspection for 99.8% of the joint areas produced. Additional refinement of software modeling algorithms is necessary; as modeling predictions for sensor actuation times were inconsistent with actual sensor data.

1.2 PROJECT OBJECTIVE

The US Navy is pursuing a larger number of components constructed of composite materials. However, the composite fabrication process is extremely variable, and infusion-related defects lead to significant rework costs and schedule interruptions. To counter these effects, this ManTech project was established to implement alternate methods and materials for improving resin distribution and component physical property.

Figure 2 – DDG 1000 Composite Structures: the Integrated Deckhouse Test Article (IDHTA), Wallops Island Surface Combat Systems Center Test Facility, and the DDG 1000 composite deckhouse and hangar

1.3 TECHNICAL APPROACH

Northrop Grumman Shipbuilding – Gulf Coast (NGSB-GC) will develop a process to address a manufacturing technology issue that if resolved, has the potential to reduce the cost and time to build and repair Navy ships. The primary objectives of the program are to:

- Develop a resin infusion process for carbon / vinyl ester composites that is predictable, repeatable and significantly reduces the defect rate experienced with current manual processes,
- Reduce the high cost of set-up labor and disposable materials associated with the current resin and vacuum distribution system, and,
- Reduce cycle times experienced with current processes.

To support these objectives, NGSS intends to leverage previous and ongoing research in these areas, take advantage of current industry teaming arrangements, and expand to form new alliances as necessary. By becoming a member of the University of Delaware, Center for Composite Materials (UD-CCM) Industry Consortium, NGSS will gain access to several attractive software packages intended to improve composite manufacturing and design techniques. In addition, NGSS will also be given the opportunity to leverage research being performed by other consortium members, and bring the results of this research to the naval shipbuilding community.

The primary focus of this program is to implement resin flow modeling technology at the NGSS Gulfport Operations facility. Naval composite structures are becoming increasingly complex, both in geometry and laminate configurations; successfully infusing these structures is becoming increasingly more challenging. There is a need to be able to accurately predict the flow of resin during these infusions to ensure that repeatable, high quality parts are the end result; previous experience has been very useful for this, but has not been fail-safe. More sophisticated tools are available to the industry, but are not currently in use at NGSS. As the prime supplier of large composite structures to the Navy, it is critical that the most sophisticated tools available in the industry are successfully proven and implemented at NGSS. For this program, NGSS intends to obtain the UD-CCM Liquid Injection Molding Simulation (LIMS) software package, have UD-CCM personnel train NGSS personnel in its use, and validate the software through the fabrication of actual 111 scale joints that have been modeled in LIMS and complete the requisite Non-Destructive Testing.

1.4 RESULTS

Two each of two types of DDG 1000 composite deckhouse joint specimens were produced as part of this project. One specimen type represented a typical deck-to-internal bulkhead composite joint – a "Simple 2D Joint". The other specimen type that was fabricated was representative of an interior deck to exterior bulkhead joint – a "Complex 2D Joint".

Each of the joint assembly, or infusion process layouts, was developed notionally. A resin flow model was developed for each joint infusion layout. This allowed the resin infusion process for each joint type to be examined in a virtual world, and modified to eliminate any potential problem areas. The software allowed the user to evaluate the resin flow through the carbon fiber reinforcement materials, and examined the function of the resin flow distribution medium (DM) and its interface with the vacuum bagging material. This allowed the users to optimize the infusion layout and address any potential problems before any material was used in the project.

The modeling software used for the project was the Liquid Injection Molding Simulation (LIMS) software that was developed, and is maintained by the Center for Composite Materials at the University of Delaware (UD-CCM). The software was provided by UD-CCM at no cost as part of their university-industry consortium, which NGSB-GC joined. They also provided on-site training to a group of NGSB-GC employees at no cost.

The purchase of a computer-based resin flow monitoring and control system was also made as part of the project. The SMARTMolding system was developed by Dr. Dirk Heider, Technical Director of UD-CCM. The hardware and software system allows a LabView virtual instrument (vi) application to be created to operate system accessories and monitor sensors placed within the materials. These SMARTMolding sensors allow the system to monitor display data related to the arrival of resin at each installed sensor, and providing the system operator with a visual indication of the resin arrival event.

SMARTMolding sensors were installed at predetermined locations for each joint infusion process. Data provided by the sensors as well as visual observations were made. This data was compared with the resin arrival times forecast by the LIMS software. The forecast resin arrival times were normalized for the different resin viscosities that were present with the eight resin infusions that were made in the project. The forecast times and the measured times for resin arrival at the various locations varied by as much as a factor of three.

- Description
  - Dell Model Optiplex 320 desktop computer
  - Touch-screen monitor
  - Keyboard
  - National Instruments LABView software-based "virtual instrument" (vi) applications provide graphical user input with the operator
  - 16 SMARTMolding sensor inputs
  - Four Type "K" thermocouple inputs
  - Ambient temperature and relative humidity sensors
  - Eight pneumatically-controlled actuators to control (optional) pneumatic pinch valves
  - Vacuum sensor and pneumatic control valve
  - Two resin scales: 1 in-flow, 1 out-flow
  - Roll-around cart

Figure 3 – SMARTMolding Equipment

1.5 CONCLUSIONS

Computer modeling and simulation of composite joint assembly processes was found to be a valuable tool to have on-hand. It allowed potential problems to be identified before beginning part fabrication.

This tool allows you to make changes to materials and part configuration in order to optimize the infusion process. It provides you with a visual display of the VARTM infusion process, allowing you to observe the part "filling" with resin. It identifies potential, undesired resin flow paths that would bypass areas of the panel's reinforcement plies – race-tracking. It gives you the capability to view internal cross-sections of the part during the infusion process.

As with any computer-based application, certain investments are required. You must purchase the software, and allow for a period of time for training, characterize the permeability of the materials in use, budget to develop, execute, and optimize the computer models, and provide input/output tools, if needed.

Use of the LIMS software was, perhaps, the primary benefit realized by NGSB-GC as part of the company's membership in the university/industry consortium. As it is a university-developed and maintained package, LIMS does not have a smooth, commercial feel to its operation. Training in its use is essential to using the software. It is relatively easy to develop 2D resin flow models using the "LEGO" package that is provided as part of the LIMS software package. LIMS can be installed on most all current personal computers that run the Microsoft Windows operating system. The only consideration that must be made relates to the microprocessor speed: the faster the processor, the faster the calculations.

In order to execute the models, it is necessary to have tested all of the infusion related materials, including the DM and reinforcement materials (carbon fiber, e-glass, etc.), and determined its permeability characteristics. In addition, the performance of the materials, as influenced by the DM and vacuum bagging materials, needs to be evaluated. If lot-to-lot variability is noted, it may be necessary to re-characterize the materials' permeabilities from time-to-time.

Development and execution of the computer models can vary from part of a day to many days, and is dependent upon the complexity, and the related precision, needed for the application. The more nodes that are contained in the model, the greater the time needed to execute the model. Simple 2D models can be executed in seconds, whereas a more complex, 3D model may take many hours to run. NGSB-GC only experienced relatively simple model executions, so no in-depth knowledge of the more complex models was gained through the project.

If used for a project, adequate time and budget must be allowed to develop and execute the models. UD-CCM was contracted to provide modeling and simulation services as part of this project. NGSB-GC employees were still learning how to effectively use the software at the conclusion of the project. UD-CCM typically provided a turn-around of their modeling and simulation activities within one week of receiving the joint infusion layout data.

When a LIMS simulation is run, a graphical presentation of the resin arrival time (in seconds) is shown. The simulation may be programmed to run until the part is completely filled, or when the resin arrives at a selected location within the part. In addition, the simulation may be paused, or it may be run repeatedly, and the forecast resin flow studied.

In order to develop presentation-grade pictures of a model, another output software package must be used. UD-CCM typically uses, and has recommended a software package called TECHPLOT. *http://www.sftek.de/*

Other options include developing a set of software tools to perform necessary file translations to allow users to import and export files between Femap and LIMS. Such was done by Material Sciences Corporation (MSC) as part of their STTR with UD-CCM. MSC provided NGSB-GC a copy of their tools for evaluation, but they were not used during this ManTech project.

2. ACCOMPLISHMENTS

A number of detailed reports were developed and delivered as part of the project:

Table 1 – Project Deliverables

NO.	TITLE	DESCRIPTION
1	1st Quarter Report	Will include quarterly accomplishments, status & issues, technology transfer status, actions, plans for next quarter, and schedule & status (Gantt chart format).
2	Transition Plan	CNST to develop with NGSS based on information provided by Smart Manufacturing Proposal.
3	2nd Quarter Report	Will include quarterly accomplishments, status & issues, technology transfer status, actions, plans for next quarter and schedule & status (Gantt chart format).
4	Deck-to-Transverse Bulkhead Simple 2-D Joint Report / Demonstration Article	Report will include the design presentation, joint production demonstration article, and NDT findings.
5	Software Acquisition & Training Report	Software Installation and Certification of up to ten (10) NGSS personnel on LIMS Software package.
6	3rd Quarter Report	Will include quarterly accomplishments, status & issues, technology transfer status, actions, plans for next quarter and schedule & status (Gantt chart format).
7	Deck-to-Side Shell Bulkhead Complex 2-D Joint Report / Demonstration Article	Report will include the design presentation, joint production demonstration article, and NDT findings.
8	~~Deck-to-Transverse Bulkhead Joint joined to a Side Shell Bulkhead Complex 3D Joint Report / Demonstration Article~~	~~Report will include the design presentation, joint production demonstration article, and NDT findings.~~ *TASK DELETED PER MOD. NO. 6 TO TASK ORDER NO. 9*
9	LIMS Update Report	Report of LIMS software performance, NGSS integration process, user compatibility, updates installed; lessons learned, and recommendations for industry use.
10	Cost Avoidance Report	Report of expected labor hours to be saved on DDG 1000 lead ship construction using cost efficient processes developed.
11	4th Quarter Report	Will include quarterly accomplishments, status & issues, technology transfer status, actions, plans for next quarter and schedule & status (Gantt chart format).
12	Development & Implementation Plan	Document containing detailed plans for each of the improvement initiatives and the associated implementation activities for each.
13	Tech Transfer	Technology Transfer Activity forums as appropriate.
14	Phase 1 – Final Report	Document containing the results/accomplishments, the improvement initiatives implemented, specifically address the process validation, and cost / benefit analysis. Will also include the technology transfer status. Elements per the Task Order; suggested format provided separately.

ACCOMPLISHMENTS

- The project team successfully used resin flow modeling and simulation software, predicting resin flow behavior and determining optimal production parameters.
- A series of common and complex composite DDG 1000 deckhouse panel-to-panel joints were produced and analyzed.
- The joints produced represent greater than 60 % of those used in the DDG 1000 composite deckhouse.
- Pilot results indicate that joints fabricated using this technology will yield a significant improvement in fabrication quality over historical rework rates, reducing historical rework rates by over 40%.

Table 2 – Project Metrics

PROJECT METRICS

Objective: Software models accurately predict infusion process								
Parameter	Baseline Value	Threshold Value	Objective Value	How to Measure	Date to be Achieved	Achievement Value	Achievement Date	How Demonstrated
Flow Front Gage Measurements	-	+/- 15% Variation	10% Variation	Flow sensors	Jan-08 (S2D) Feb-08 (C2D)	Not Achieved	Not Achieved	Predicted models are compared to data captured during infusion
Objective: Achieve Satisfactory Physical Characteristics								
Parameter	Baseline Value	Threshold Value	Objective Value	How to Measure	Date to be Achieved	Achievement Value	Achievement Date	How Demonstrated
Joints Meet UT Inspection	60%	76%	>76%	Direct Measurement	Jan-08 (S2D) Feb-08 (C2D)	100% 99.8%	Feb-08 Mar-08	Joint Fabrication
Objective: Reduce Joint Infusion-related Rework Cost								
Parameter	Baseline Value	Threshold Value	Objective Value	How to Measure	Date to be Achieved	Achievement Value	Achievement Date	How Demonstrated
Cost	60%	36%	<36%	EVMS	Jul-08	15%	Jul-08	Cost comparison to previous rework

3. PROJECT TASKS

3.1 TASK 1 – SOFTWARE ACQUISITION AND TRAINING

Statement of Work Tasking

- The Contractor shall joint the University of Delaware, Center for Composite Materials (UD-CCM) Industry Consortium
  - Obtain LIMS software at no cost
  - Receive LIMS training for up to ten employees
  - Develop a model and prediction for each of the infusions

Accomplishments

- NGSB-GC joined the University-Industry Consortium
- NGSB-CG received LIMS software and training
  - LIMS Software received October, 2007
    - Software expired 31Aug08
  - LIMS Software installed on users' computers 29Jan08
  - LIMS Training, Part 1 – October 9 – 10, 2007: 11 employees trained
    - Introductory training
    - Simple examples used
  - LIMS Training, Part 2 – April 21 – 22, 2008: 8 employees trained
    - Refresher training
    - Advanced user training, including model development
    - "Smart Manufacturing" joints, "Hangar Stiffener" panel, and LSSTA deck panel examples used
- NGSB-GC reviewed models developed by UD-CCM in support of the project

3.2 TASK 2 – MODELING AND SIMULATION TASK

Statement of Work Tasking

- The Contractor shall contract with the University of Delaware, Center for Composite Materials (UD-CCM) Industry Consortium to support modeling and simulation of production demonstration articles...

Accomplishments

- NGSB-GC contracted with UD-CCM for modeling and simulation services
  - Sketch 5693-001: "Simple 2D Joint"
  - Sketch 5693-002: "Complex 2D Joint"
    - Upper Joint
    - Lower Joint
- Weekly teleconference discussions held

- NGSB-GC provided UD-CCM with notional infusion layouts and joint details
- UD-CCM provided
  - Analysis of notional joint layouts
    - Identified potential problems
    - Estimated time to perform the resin infusion process
  - Recommended infusion layouts
- M&S resin arrival times
  - Estimates were as much as 3x greater than measured times
  - Provided guidance in establishing resin gel time formulations
- Observed resin arrival times were used to adjust material permeability value assumptions

3.3 TASK 3 – PROCESS VALIDATION TASK – SIMPLE 2D JOINT

Statement of Work Tasking

- The Contractor shall provide engineering, designing, and manufacturing services for the production of... simple 2-D joint production demonstration articles representative of the DDG 1000 deckhouse deck-to-transverse bulkhead 2-D joint
  - Develop optimal infusion setup
  - Collect infusion data
  - Perform non-destructive testing to validate its successful infusion

Accomplishments

- NGSB-GC fabricated and assembled two "Simple 2D Joint" specimens
- Infusion data was collected using SMARTMolding equipment
- Each joint was inspected to, and met current DDG 1000 joint critical flaw size criteria

Figure 4 – Simple 2D Joint Specimen

3.4 TASK 4 – PROCESS VALIDATION TASK – COMPLEX 2D JOINT

Statement of Work Tasking

- The Contractor shall provide engineering, designing, and manufacturing services for the production of... complex 2-D joint production demonstration articles representative of the DDG 1000 deckhouse deck-to-sideshell bulkhead 2-D joint
  - Develop optimal infusion setup
  - Collect infusion data
  - Perform non-destructive testing to validate its successful infusion

Accomplishments

- NGSB-GC fabricated and assembled two "Complex 2D Joint" specimens
- Infusion data was collected for lower joint infusions using SMARTMolding equipment
- Each joint was inspected to current DDG 1000 joint critical flaw size criteria
  - Three small areas on one of the four joints infused as part of this task failed to meet the inspection criteria (22.125 in² out of 10,742 in² "Complex 2D" joint areas)

Figure 5 – Complex 2D Joint Specimen

3.5 TASK 5 – PROCESS VALIDATION TASK – COMPLEX 3D JOINT

Statement of Work Tasking

- The Contractor shall fabricate eight composite panels to support engineering, designing, and manufacturing services for... complex 3-D joint production demonstration articles representative of the DDG 1000 deckhouse deck-to-transverse bulkhead joint joined to a side shell bulkhead
  - Two side shell panels
  - Two deck panels
  - Four internal bulkhead panels

Accomplishments

- NGSB-GC fabricated all panels
- Specimen assembly requirement eliminated by Modification No. 06 to Task Order No. 09

3.6 TASK 6 – COMPOSITE SPECIMEN TRANSFER TASK

Statement of Work Tasking

- Development and Shipment of 2D Complex Joint Specimen: Cut, shape, de-burr, package, and ship to the Office of Naval Research (ONR) one display section of an existing 2D Complex Joint Specimen
- Packaging and Loading 2D Simple and 2D Complex Joint Specimens: Package and load for shipping the four specimens fabricated in Tasks 3 & 4; package and load for shipping the two side shell panels... and the two deck panels... fabricated to support the 3D Complex Joint Task (Task 5)... The shipment will be sent to the University of California – San Diego to support the ONR Blast Mitigation Program
- Packaging and Shipment of Four Composite Panels: Package, load and ship four composite internal bulkhead panels... fabricated to support the 3D Complex Joint Task (Task 5) to the General Dynamics-Electric Boat facility to support another ONR project

Accomplishments

- Shipment of all specimens and panels completed
  - ONR display specimen shipped 15 July 2008
  - UCSD specimens and panels shipped 21 July 2008
  - GD panels shipped 10 July 2008

3.7 TASK 7 – COST AVOIDANCE TASK

Statement of Work Tasking

- The contractor shall report expected labor hours to be saved on DDG 1000 lead ship construction using cost efficient processes developed under this effort

Accomplishments

- Cost Avoidance Report routed for review and approval 02Jul08
- Estimated cost avoidance for lead ship (based upon project results):
  - Estimated Lead Ship Cost Avoidance = **5,788 HR**,
  - Estimated Cost Savings = = **75.0%**
- Project Goal: 40% Reduction of Threshold Value

4. TECHNOLOGY TRANSFER STATUS

Project overviews were presented at various meetings and conferences:

- Fall, 2007 TCC and ESC, Orlando, Florida, October 9, 2007
- SSAI LIPT, ShipTech, Biloxi, Mississippi, February 13, 2008
- Joint Defense Manufacturing Panel, Arlington, Virginia, August 7, 2008

Technical Presentations relating to the project were made at two other conferences:

- Spring TCC and ESC Meeting, Arlington, Virginia, June 4, 2008
- DDG 1000 IPT Meeting, Johnstown, Pennsylvania, June 12, 2008

An abstract has been submitted to present the project at the spring 2009 ShipTech conference.

5. IMPLEMENTATION STATUS

The technology gained from this project has been implemented for use on the DDG 1000 composite deckhouse and hangar program.

TASK 3.0: Process Validation Task – Simple 2D Joint

DDG 1000 Large-Scale Shock Test Article (LSSTA)

Workbook No.	Title
XDD14L7027M-MFG	Assy. – Join 04 Deck to L2 Bhd
XDD14L7027N-MFG	Assembly - Sub-assembly A: Join T1 Bhd (lower) to L1 (lower) Bhd
XDD14L7027P-MFG	Assembly - Sub Assembly B: Join T1 Bhd (upper) to L1 (upper) Bhd.
XDD14L7027S-MFG	Assembly - Join Aft Bhd to Assy.
XDD14L7027U-MFG	Assembly - Join Sub-Assembly A (lower) to Assy.
XDD14L7027V-MFG	Assembly - Join Sub-Assembly B (upper) to Assy.
XDD14L7027W-MFG	Assembly - Join Fwd VSR Strut to Assy.
XDD14L7027X-MFG	Assembly - Join Aft VSR Strut to Assy.
XDD14L7027Y-MFG	Assembly - Join IFF Ligament to Assy.
XDD14L7027AA-MFG	Assembly - Join 07 LVL DECK to Assy.

DDG 1000 Program UT Calibration Blocks

Workbook No.	Title
XDD14L1037F-MFG	UT Wedge Block Joint Reference Standard - Assembly

DDG 1000 Program Static and Fatigue Test Articles

Workbook No.	Title
XDD14L1056G-MFG	Interior Bhd to Side Shell Joint (Static) - Assembly #1
XDD14L1056H-MFG	Interior Bhd to Side Shell Joint (Static) - Assembly #2
XDD14L1056J-MFG	Interior Bhd to Side Shell Joint (Static) - Assembly #3
XDD14L1056K-MFG	Interior Bhd to Side Shell Joint (Fatigue) - Assembly #1
XDD14L1056L-MFG	Interior Bhd to Side Shell Joint (Fatigue) - Assembly #2

TASK 4.0: Process Validation Task – Complex 2D Joint

DDG 1000 Large-Scale Shock Test Article (LSSTA)

Workbook No.	Title
XDD14L7027R-MFG	Assembly - Join Front Bhd to Assy.
XDD14L7027T-MFG	Assembly - Join Oblique Bhd to Assy.
XDD14L 7027Z-MFG	Assembly - Join Side Shell to Assy.

DDG 1000 Program UT Calibration Blocks

Workbook No.	Title
XDD14L1037L-MFG	UT Type III Joint Reference Standard - Assembly w/Overwrap

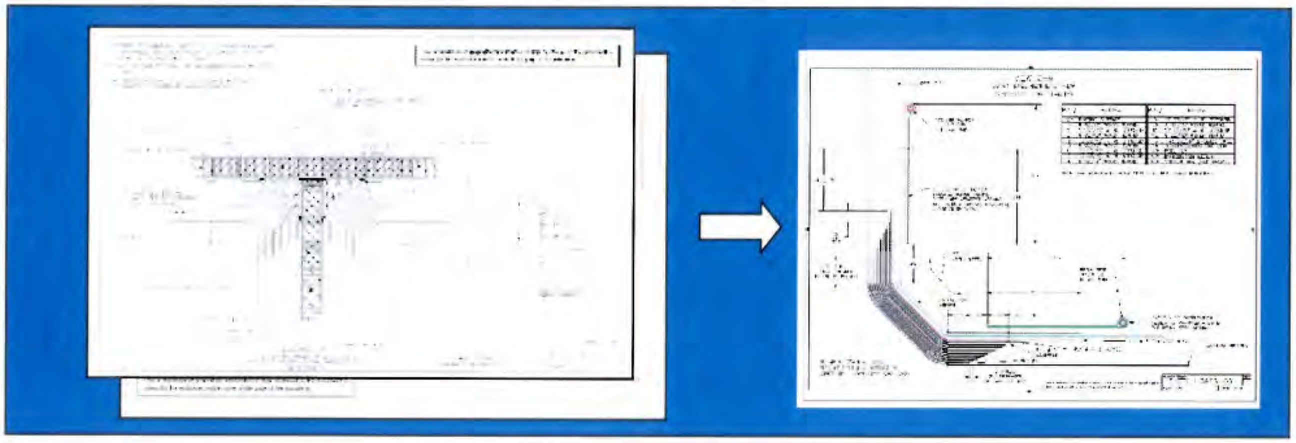
DDG 1000 Program Static and Fatigue Test Articles

Workbook No.	Title
XDD14L1055G-MFG	Side Shell to Deck Joint (Static) - Assembly #1
XDD14L1055H-MFG	Side Shell to Deck Joint (Static) - Assembly #2
XDD14L1055J-MFG	Side Shell to Deck Joint (Static) - Assembly #3
XDD14L1055K-MFG	Side Shell to Deck Joint (Fatigue) - Assembly #1
XDD14L1055L-MFG	Side Shell to Deck Joint (Fatigue) - Assembly #2

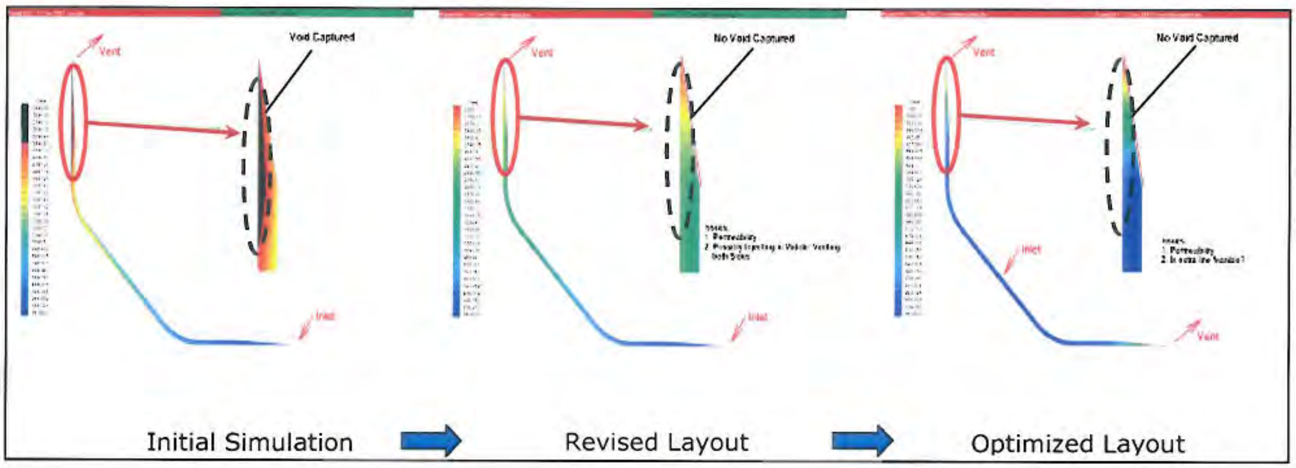
Figure 6 – Technology Implementation on the DDG 1000 Composite Deckhouse and Hangar Program

Transition of the technology has been used successfully in support of various program related projects. The Simple 2D Joint process has been used to fabricate over 192 linear feet of composite-to-composite joints in the DDG 1000 Large Scale Shock Test Article (LSSTA), with no rejects. This same information has also been used in the fabrication of various test articles with similar layouts, but with joint overwrap thicknesses as great as one inch. The Complex 2D Joint process has been used in similar production tasks, with no rejects.

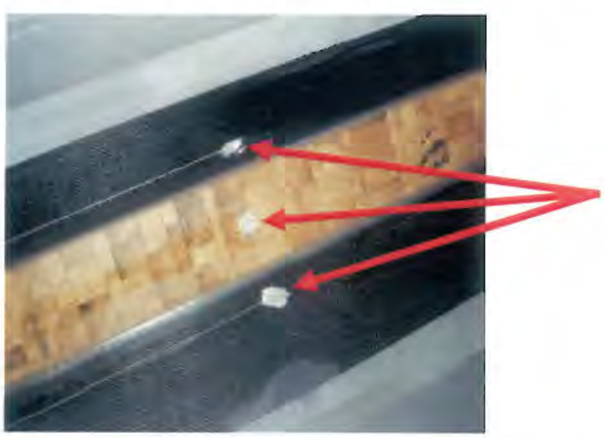
6. SMART MANUFACTURING PROCESS SUMMARY



1. Joint design and notional joint infusion layout developed based on joint scantlings.



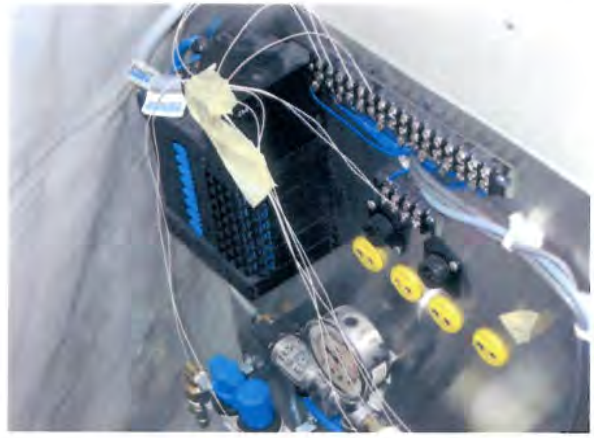
2. Joint design and infusion layout evaluated: Model developed for joint, and simulations are run. Infusion layout is optimized.
3. Panels are assembled together; joint wedge block installed.
4. SMARTMolding sensors are fabricated, and installed throughout joint lay-up.



SMARTMolding Resin Flow Sensors Installed on joint wedge block

5. Joint reinforcement plies are installed. The remainder of the SMARTMolding sensors are installed. The joint is prepared for infusion.

6. Sensor lead wires are connected to the SMARTMolding equipment.



7. Joint infusion process performed. SMARTMolding sensor data monitored on the display, and data is recorded.

8. The SMARTMolding data is analyzed and charted.

Time of Day	Elapsed Time	Sensor 1	Sensor 2	Sensor 3	Sensor 4
9:54:00	0:00:00				
9:54:01	0:00:01				
9:54:02	0:00:02				
9:54:03	0:00:03				
9:54:04	0:00:04				
9:54:05	0:00:05				
9:54:06	0:00:06				
9:54:07	0:00:07				
9:54:08	0:00:08				
9:54:09	0:00:09				
9:54:10	0:00:10				
9:54:11	0:00:11				
9:54:12	0:00:12				
9:54:13	0:00:13				
9:54:14	0:00:14				
9:54:15	0:00:15				
9:54:16	0:00:16				
9:54:17	0:00:17				
9:54:18	0:00:18				
9:54:19	0:00:19				
9:54:20	0:00:20				
9:54:21	0:00:21				
9:54:22	0:00:22	0.06			
9:54:23	0:00:23	0.07			
9:54:24	0:00:24	0.08			
9:54:25	0:00:25	0.09			
9:54:26	0:00:26	0.10			
9:54:27	0:00:27	0.11			
9:54:28	0:00:28	0.12			
9:54:29	0:00:29	0.13			
9:54:30	0:00:30	0.14			
9:54:31	0:00:31	0.14			
9:54:32	0:00:32	0.15			
9:54:33	0:00:33	0.15			
9:54:34	0:00:34	0.16			
9:54:35	0:00:35	0.16			
9:54:36	0:00:36	0.17			
9:54:37	0:00:37	0.17			
9:54:38	0:00:38	0.17			
9:54:39	0:00:39	0.17			
9:54:40	0:00:40	0.18			
9:54:41	0:00:41	0.18			
9:54:42	0:00:42	0.18			

7. REVISION HISTORY

Rev	Date	Section	Description
-	10/07/08	All	Initial Issue