AMPTIAC

Special Issue:

Ships

Navy Experts Explain the Newest Material & Structural Technologies
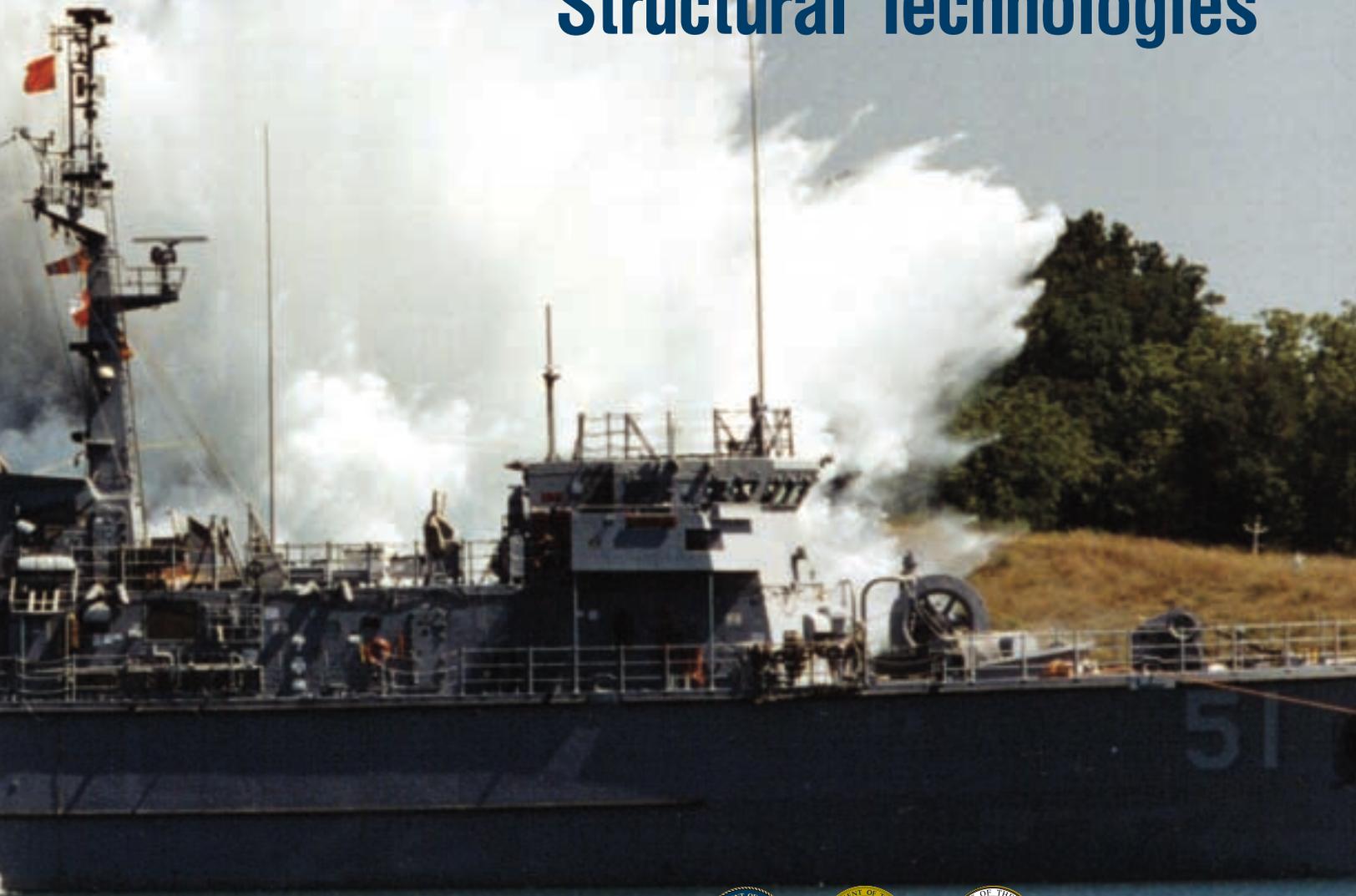
DARPA

The issue you hold in your hands has been 14 months in the making. It began with a simple idea: turn the spotlight on the age-old art of building ships. We wanted to show the exciting new technologies that are offering novel materials for ship construction, changing the way ships are built, and indeed creating one of the most fundamental shifts in Navy combatants since steel replaced wood.

This simple mission turned out to be much more complex. The project underwent a number of different iterations, but finally settled in and came together. It has been a labor of love for yours truly, for I really do believe that even though airplanes and tanks often grab the spotlight, Navy ships are still the most challenging structural and materials engineering systems fielded in today's military. Nothing has the complexity, impact, size, and sheer force of a fighting vessel, nor can many things capture the imagination in quite the same way.

So here it is, finally, and I am thankful that it is done. Not just because it is off my desk and I can get on to the next project, but we are proud because AMPTIAC has compiled something that probably has not existed before: an overview of the newest technologies being incorporated into structures and materials for use aboard Navy combatants. And the people providing the perspective are the experts at the Office of Naval Research, NSWC-Carderock, and the Naval Research Lab. You won't find this level of detail, variety, and expert content focused on this subject anywhere else.

That all being said, there is one critical feature of this publication that needs some attention: the DOD center behind it. Some of you out there have been reading this publication for seven years now. You undoubtedly remember about two years ago when we shifted over to our current layout format and full color reproduction. You also have probably noticed that we are publishing these large special issues fairly often. It is all a part of our mission to bring you the most in-depth, focused, and technologically exciting coverage of Defense materials and processing advances available anywhere.

But the side effect of the more noticeable and attention-grabbing Quarterly, is that AMPTIAC itself has lost some attention. The reality is that the center has grown with numerous projects, focused reports, and database efforts over the past few years, but there are many out there that may read this publication and not even know that the center exists.

We want to put more emphasis on the other efforts AMPTIAC is involved in, and let our customers and potential customers know that we are here for you. We help with questions, assist in materials selection, and provide consultation on a variety of materials and processing-related issues. We have more than 210,000 DOD technical reports in our library and direct access to hundreds of thousands more throughout DOD, DOE, NASA, and other US Government agencies. We have dozens of focused reports tailored to specific technology areas and many more compiling vast amounts of data into handbook-style resources.

The basic message here is to take note of this magazine, read it, and enjoy. But if you think AMPTIAC is just the Quarterly, Think Again.

Wade Babcock
Editor-in-Chief

Editorial:
There's More to AMPTIAC than the *Quarterly*

http://iac.dtic.mil/amptiac

Intelligent Processing and Inspection of Naval Composites

Roger M. Crane, Composite Materials Section Head
Structures and Composites Department
Carderock Division, Naval Surface Warfare Center
West Bethesda, MD

John W. Gillespie, Jr., Dirk Heider, Shridhar Yarlagadda, and Suresh G. Advani
Center for Composite Materials, University of Delaware
Newark, DE

INTRODUCTION

Composite materials are being used in increasing amounts in a variety of Navy applications based on their stiffness, strength, reduced weight, and corrosion-free capabilities. Additional properties such as fire and ballistics resistance, signature reduction, and enhanced communications make them attractive for integrated structures known as multifunctional composite materials (MCMs) that will be able to address the needs of future Navy vessels. (The long-term plan for Navy ship evolution is called "Navy After Next.")

Processing methods are being developed that can fabricate large-scale components with built-in, tailored multifunctional capabilities. Intelligent process control (IPC) is critical to fabricate, integrate and scale-up complex, net-shape, multifunctional composite materials reliably and in a cost effective manner. The components of intelligent process control – design and analysis, modeling and simulation, sensing and control – need to apply a cradle-to-grave philosophy to address not only fabrication but also inspection and health-monitoring issues. With the use of intelligent process control and creation of multifunctional materials, composites represent the key to future ships systems including DD(X) (*Zumwalt*-class) destroyer and littoral combat systems (LCS).

History/Background

Several large-scale composite structures have been implemented in the US Navy and in other partner countries. The main advantages of fiber reinforced plastic (FRP) structures include lightweight and multi-functional capabilities such as reduced signature and non-magnetic hull sections. The major applications include topside structures (for example the Advanced Enclosed Mast Sensor System (AEM/S) and the Director's Room for *Arleigh Burke*-class destroyers) as well as complete hull solutions (Coastal Mine Hunter [MHC 51], P-960 KNM *Skjold*, and *Visby*-class corvette).

The most significant composite structures manufactured for the US Navy are the AEM/S System and the MHC 51-class coastal mine hunter hull. The AEM/S system was installed on USS *Radford* (DD 968) in October 1997. This structure is approximately 95 feet tall and 30 ft. wide at its midsection. This,

the largest topside composite structure aboard a US Navy ship and weighing some 40 tons, was fabricated using the Seemann Composite Resin Infusion Molding Process (SCRIMP®) (Figure 1, left). Figure 1, right shows the composite hull section of the mine hunter fabricated at Avondale Shipyard. This solid and continuous monocoque structure has a length of 188 ft and a total displacement of 895 metric tons.

The Swedish Navy put the *Visby*-class corvette (seen in Figure 2) in service in 2000. The vessel is built of sandwich-construction carbon/vinyl-ester, which ensures high strength at low weight with integrated stealth qualities. The total length of the ship is approximately 236 feet at a displacement of 600 tons. *Skjold* is the Royal Norwegian Navy's first fast patrol craft/littoral combat ship of the *Skjold*-class and is currently being evaluated by the US Navy. The ship is based on a catamaran hull where lift fans blow air into an air cushion between the hulls. The structure is built with FRP sandwich using uniaxial glass fiber and carbon laminates with vinyl-ester or polyester resin. Polyvinyl chloride (PVC) core material is used in main structural elements below main deck and polymethacrylimide (PMI) core material is used elsewhere and for the complete superstructure. The total length of *Skjold* is approximately 157 feet at a displacement of 260 tons.

These large-scale composite structures have been built using liquid composite molding (LCM) techniques. LCM allows the dry lay-up of the materials in a mold, thus permitting integration of various functional materials into the structure. The preferred LCM fabrication method for large-scale application is vacuum-assisted resin transfer molding (VARTM, as seen in Figure 3). Here, a stack of dry fiber reinforcements, usually known as a preform, is placed over a tooling surface and is enveloped and sealed with a flexible plastic bag by drawing a vacuum through a vent. This compacts the preform and, as a result, the preform conforms to the tool surface. The resin is injected and drawn into this assembly through openings known as gates, due to the vacuum in the compacted preform, by connecting the resin reservoir to the tooling. The pressure difference of nearly one atmosphere between the resin reservoir and the vacuum vent port drives the resin into the preform to impregnate the empty spaces between

Figure 1. Left, The AEM/S System on USS *Radford* (DD968) and Right, Composite Hull of MHC 51.

the fibers. Flow enhancement networks such as flow runner channels and distribution media (layers of fabrics with relatively low flow resistance) are used to accelerate mold filling and saturate the preform before the resin gels. The resin flowfront in VARTM is three-dimensional; it moves through the thickness as it spreads through the plane of the part. For complex geometries and when various functional materials are used the flow front can become complex and difficult to control. After full infusion, the resin gels and cures at room temperature creating the final part geometry. Lower tooling costs and the room temperature cure make VARTM especially favorable in manufacturing large composite parts such as ship hulls, bridges, and wind turbine blades.

MULTIFUNCTIONAL COMPOSITE MATERIALS AND STRUCTURES

Efforts sponsored by the Office of Naval Research (ONR) are laying the foundations of an affordable and sustainable fleet for the 21st Century. As a result, the *Navy After Next* will consume less fuel per hour, require fewer operating personnel, and spend less time in dry dock for maintenance than any fleet before it. It is even expected that procedures undertaken by personnel to primarily check-out systems will be increasingly replaced by "condition-based maintenance" in which sensors report on the integrity of machines and materials and provide sufficient data for actual hands-on maintenance and repair only when needed.

Advanced surface combatant designs will incorporate and extend many features currently in experimentation on today's ships, such as *Radford*, USS *Yorktown* (CG 48), DDG 51, etc. Indeed, once these features are developed to the application stage, many of them can be retrofitted to greater or lesser extent in today's ships at major maintenance

and overhaul milestones during their service lives to increase survivability, system reliability, and ship service life. Foremost among the changes in ship design that advancing technology will permit and encourage is multifunctional composite structures.

The technology of multifunctional composite structures (depicted in Figure 4) will enable lightweight energy-absorbing designs for mine/blast and ballistic protection; fire-hardened sandwich constructions; embedded and conformal sensors and actuators for communications, health monitoring, and prognostics; as well as material properties and specific shaping capability that will help meet future signature goals. Such structures will also reduce weight, corrosion, and maintenance requirements, as well as allow modular design approaches.

Composite structural designs for blast, ballistic, and fire protection are currently being considered for both ground vehicle structures (Army Future Combat Systems) and ship topside structures. Co-injection resin transfer molding (CIRTM) -based processes have been demonstrated for the director's room of DDG 51, enabling multifunctionality for structural and fire-resistant performance. Fully integrated instrumentation and automation can be achieved using embedded and distributed networked sensors, actuators, and microprocessor controls, thus enabling reduced crew size. Damage control will also be a primary focus of automated systems, as it is a major determinant of crew size. Composite materials and structures will also enable specific geometric shaping, treatment, and reflection or absorption characteristics of exposed structure. Introducing composites will also allow downsizing or elimination of the mast(s); integration with other topside components such as low-observable intakes or uptakes; and fully enclosed small craft handling equipment, hangars, speakers, lights, and doors. The aggregate result of these changes would be a significant advancement in the capabilities of future naval surface platforms in an affordable manner.

Significant research is being conducted in the various desired functionalities, such as ballistics, fire, health monitoring, signature, etc. The major barriers to implementation in ship structures are the ability to integrate these functionalities into the structure and the associated manufacturing issues. Intelligent process control is key to enabling system integration and manufacturing, not only to achieve the

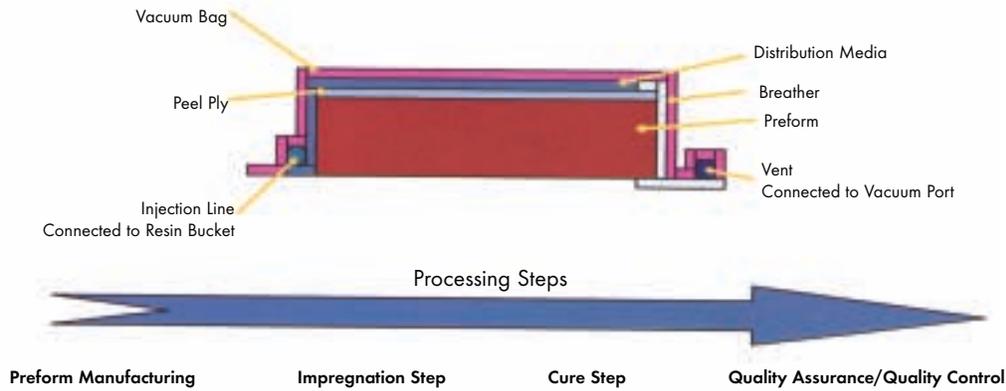**Figure 2.** *Visby* and *Skjold* During Sea Trials.

Figure 3. Schematic of the VARTM Process.

desired performance, but also for quality, repeatability, and affordability. The ultimate goal is an automated intelligent manufacturing process, where the desired performance characteristics can be obtained through a "plug-and-play" approach within the constraint of liquid molding process technology.

INTELLIGENT PROCESSING

Multi-functional composite materials have to be manufactured using 21st-century techniques based on the VARTM process, enabling integration of the desired capabilities into the final part. Intelligent processing can be defined as the cradle-to-grave use of various scientific and monitoring tools such as science-based numerical simulations, sensors to gather information, and actuators to automatically correct for unforeseen disturbances during processing. In addition, the introduction of automation will reduce labor, improve repeatability, and increase yield. ONR has established the Advanced Materials Intelligent Processing Center (AMIPC) at the University of Delaware whose goal is to adopt and move liquid composite molding processes towards automation and cost effectiveness by integrating science-based models into the decisions for process control. The center is focused on the development of software and hardware tools and their integration and implementation to extend the processing science in order to improve quality and affordability of multifunctional composite structures for Naval applications. This will be accomplished using sensors, science-based simulations, and process control to advance composite manufacturing with LCM. This effort can be divided in four categories as shown in Figure 5.

The first component of intelligent process control is process design to manufacture composite parts with the desired performance in an affordable manner. This requires an understanding and modeling of the process physics as the basis for virtual manufacturing simulations and new process innovations. Next, an integrated approach to part and mold design, process optimization, and formulation of control actions is needed. Critical to both process
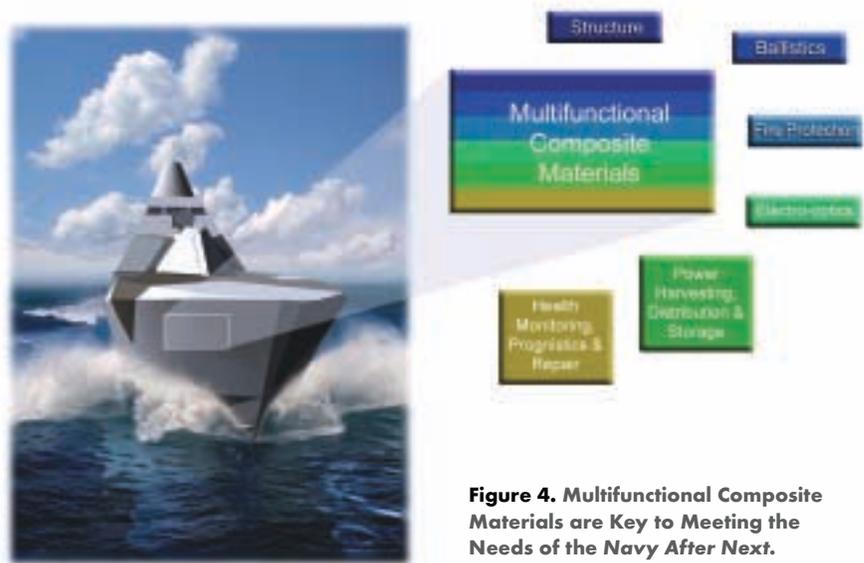

Figure 4. Multifunctional Composite Materials are Key to Meeting the Needs of the *Navy After Next*.

control and inspection is adequate sensor technology for process monitoring. Finally, inspection and health monitoring will ensure the quality and properties of the composite material in service. Multifunctional requirements will cause changes in reinforcement schemes, resin selection, and integration of various materials/devices, all of which require virtual manufacturing simulations to address process design and optimization.

PROCESS DESIGN

The need for process design arises from two main factors. First, as one moves the injection location for the resin, the flow pattern will change and will influence the time to fill the mold by orders of magnitude and create scenarios ranging from complete saturation of the fibers by the resin to large-scale dry spots resulting in scrap. Second, for very large composite structures, multiple inlet gates are required to ensure complete wet-out of the part prior to gelation of the resin. Selection of the distribution media, preforms, and gate and vent locations are typically based on past experience for similar applications. However, analytical and finite element analysis (FEA) simulations can be used to calculate the parameters (as a function of resin, preform, and distribution media properties) and to optimize sequential injection spacing and location.
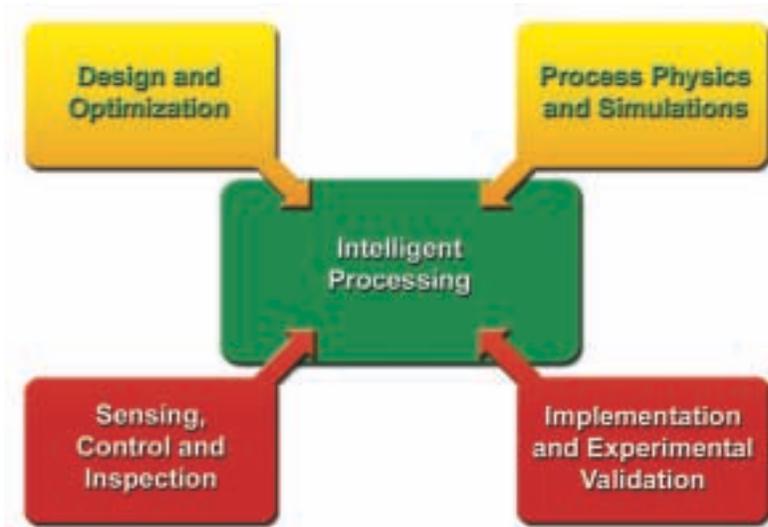
Figure 5. Key Components of Intelligent Processing Needed for 21st-Century Manufacturing.

With the integration of new materials, the preform flow characteristics can change by orders of magnitude. Advanced infusion schemes such as interlaminar flow media may have to be applied and the injection spacing has to be adjusted. Simple design tools (Figure 6) can support the basic decisions currently made by the expert engineer. The systems can be used to reduce prototyping efforts and reduce risk if preform material is being changed. This will allow for faster integration of more affordable or improved materials.

PROCESS PHYSICS AND SIMULATIONS

Development of a virtual manufacturing platform is one of the goals of intelligent processing. The key ingredients to creating such a platform are formulation of process models (based on the observed physics of the process and relevant assumptions) and incorporation of such models in a computer simulation (that can mimic the process reality in an effective and efficient manner). Under the AMIPC program, the Center for Composite Materials at the University of Delaware (UD-CCM) has developed simulation tools such as LIMS (Liquid Injection Molding Simulation) and SLIC (Simulation-based Liquid Injection Control). LIMS can describe the resin impregnation physics in most liquid com-

Database   Material Selection

Design Interface

Figure 6. Process Design Tools and Supporting Materials Databases Enable Virtual Manufacturing for Intelligent Process Control

posite molding processes and is used to develop the optimal tool and process design before fabricating the tool. The simulation also has a user interface, which allows for easily changing gate locations in the tool or adding distribution media at different locations in the VARTM process. This has made it possible to perform "trial and error" process runs on the virtual platform which converge toward the best possible process design. The simulation has been continuously tested against experiments to validate the process physics as new phenomena encountered in the process are incorporated into the simulation. Examples include the injection and resin flow simulations for composite armor and a composite twisted rudder, as shown in Figure 7. Numerical efficiency is also a key parameter, as the simulation tool will be used for design and optimization studies that would require one to explore many mold filling scenarios before selecting the optimal one as dictated by the criteria. SLIC was developed to allow the computer to search and find the best solution using the virtual platform and genetic algorithms. SLIC links its design with a common software interface that directly controls manufacturing, allowing for automation of the process.

INTEGRATED SENSING

All design and optimization studies assume an "ideal" known value of preform permeability. In practice, variation in the flow due to the variability in the preform lay-up and permeability is observed. These variations in processing occur not only during filling but also during curing of the composite. Flow sensors are important to effectively control the flow in spite of this variability. Another concern is monitoring the health of the composite after it has been manufactured. Hence sensors that can address these issues are essential to the intelligent processing framework.

Over the years, many sensors have been developed and tested. One of the earlier successes was the SMARTweave sensor grid, which comprises two orthogonal sets of conductive filaments separated by one or more fabric layers placed within the composite mold. As resin fills the mold and the gaps between the filament planes, electric circuits are completed. Associated instrumentation detects the signals and can determine the resin location and cure state. The DC-based system can be integrated into the tool, allowing re-use of the many sensors required for large parts. The system monitors resin flow well and has limited resolution for cure monitoring.

Recently, time domain reflectometry (TDR) sensors have been developed and evaluated for both resin flow monitoring and cure. TDR involves sending high voltage step-pulses into a transmission line, and detecting reflections returning from the impedance discontinuities within the line. Any dielectric and/or geometrical discontinuity in the line changes the characteristic impedance, and introduces a voltage reflection at a particular time and magnitude. The system accurately measures distributed parameters such as the resin flow position and the degree of cure, and compares favorably to data collected by charge coupled device (CCD), Fourier transform infrared spectroscopy (FTIR), and differential scanning calorimetry (DSC). (See Figure 8). The
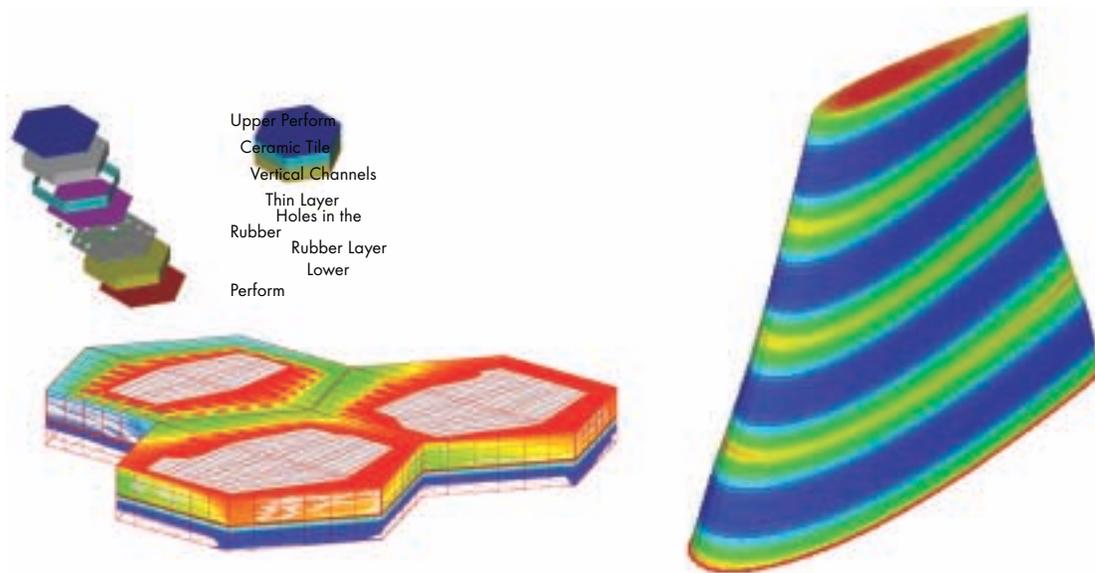
Figure 7. LIMS Simulates the Filling Stage of LCM Processes for Complex 3-D Structures.

transmission line can be embedded into the part or on the surface or integrated into the tooling making it reusable for many process runs. The system is a non-contact sensor allowing detection through gel coats commonly applied on the mold surface.

TDR sensors are unique due to the fact that they are lineal sensors and can be used to interrogate changes along the entire length of the sensor, rather than at a point (for example: fiber optic sensors). This reduces the number of sensor lines and associated acquisition hardware. TDR sensors can also be used for health monitoring since they can be used to measure strain, observe crack propagation, and detect defects in composites. This technology provides a true cradle-to-grave solution for process and health monitoring and is currently being optimized for ship structure applications.

PROCESS CONTROL, AUTOMATION AND QA/QC

Due to variations in preform permeability, preform lay-up, and resin chemistry, the filling and curing scenario may vary from one part to the next in the same batch. Engineering supervision is required during the resin infusion process to open the injection gates at the right time intervals. Often the only feedback for

the engineer is a visual surface wet-out measurement. In general, during surface injection with a distribution media, the flowfront at the tool surface lags behind the flowfront at the distribution media surface due to the time it takes to penetrate the preform. For thick-section composite parts, the distance between the flowfronts on opposite surfaces can be of the same size as the typical distance used between sequential injection gates. As a result, premature opening of an injection port will result in large dry-spot development under the injection lines. Delayed opening of an injection line significantly extends the overall cycle time. New applications where part thickness, resin properties, or preform characteristics vary may require costly trial and error process development to optimize the sequential opening. Under the AMIPC program, UD-CCM has developed methodologies to introduce control actions in LCM processes.

An automated system, called SMARTMolding, has been developed to completely automate and monitor the process. Injection gates are opened in sequence when mold-mounted flow sensors detect the tool-surface flow front at a particular gate. The process is completely autonomous and does not depend on resin permeability variations, changes in preform characteristics, or other
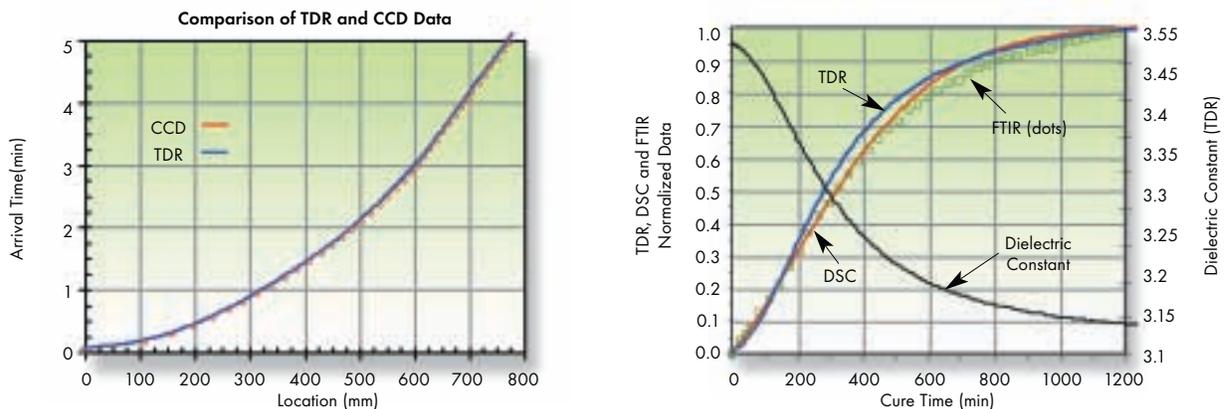

Figure 8. Time-Domain Reflectometry Sensors Used in VARTM Processing.

Figure 9. SMARTMolding Allows Automation of all VARTM Processing Steps.

processing factors. In addition, the SMARTMolding system does not require costly trial-and-error development of a conventional sequential scheme and therefore does not demand the engineering knowledge normally required during resin impregnation. However, the number of inlets and sensor locations must be specified. The automation capabilities enable monitoring of cycle times for all processing steps, sensing of the important process parameters through embedded sensors, and quality assurance/quality control (QA/QC) of the complete process. Figure 9 shows one SMARTMolding workcell implemented at United Defense-York as part of a larger plant setup for automated VARTM production. The different workcells are connected and the lay-up stations are semi-automated creating a first step towards a 21st-century composite manufacturing environment.

INSPECTION AND HEALTH-MONITORING

Once a composite structure has been successfully manufactured, it becomes necessary to have methods to determine the structural integrity of the component during the service life. This is not a trivial matter. Two characteristics make most conventional composite NDE techniques impractical for these structures: size and environment. In the case of the AEM/S system and similar masts, each structure has thousands of square feet of surface. In addition, the construction has typically been a core configuration with multiple layers, which can have thicknesses of up to several inches. The thickness issue causes many problems with most NDE techniques.

A vibration-based inspection method, developed at Carderock Division, Naval Surface Warfare Center and the United States Naval Academy, has been successfully used to inspect large-scale composite structures of both sandwich construction and rib-stiffened configurations. This technique is called the Structural Irregularity and Damage Evaluation Routine, or SIDER. This vibration-based method is capable of locating areas of structural degradation and specific damage in sandwich and rib-stiffened structures.

The SIDER inspection has been used on a .5-scale composite corvette hull section (Figure 10). This structure is a rib-stiffened configuration with varying sizes of hat stiffeners, multiple composite decks, bulkheads, and cutouts. The structure was about

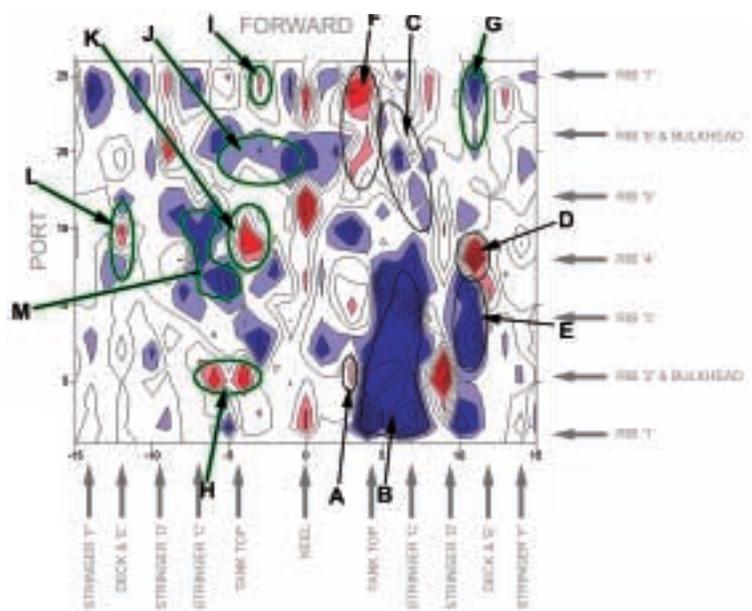**Figure 10.** SIDER Used to Find Damage in Composite Ship Structures.

Figure 11. Technology Transfer to the DOD Industrial Base.

Fundamental Science Base

System Development and Validation

30 ft long 19.5 ft wide and about 11 ft high from the keel to the top deck. The SIDER inspection was performed prior to and following the shock testing. In general, significant levels of damage occurred. The SIDER testing was able to identify all of the areas on the structure that contained damage, indicated by the labeled areas in Figure 10.

This damage was in the form of delaminations, debonding of ribs or stiffeners, separation of decks or bulkheads, and laminate cracking. All of these areas were verified either visually or through ultrasonic inspection (indicated with lettered callouts in Figure 10). It should be noted that all of the damage located by ultrasonic inspection was also identified by the SIDER inspection. Similar inspections using SIDER have been performed on an all-composite bridge deck since 1997 on an annual basis.

Capabilities to inspect large-scale composite structures now exist. Continued advances are expected as new internal and external sensors are developed and inspection technology evolves. One future possibility is that the two functions (health monitoring and communication) will be broadcast on different frequencies but share the same fiber connections throughout a ship.

TECHNOLOGY TRANSFER

While there has been considerable investment in basic and applied research, resources required by the DOD and Navy Industry base to transition these technologies into practice are in many cases insufficient. UD-CCM has a strong history of collaboration and technology transfer to the industry, having been associated with more than 200 companies over its history. The AMIPC program has developed several technologies ranging from an understanding of basic physical principles all the way to software and hardware solutions that can be implemented at the factory floor. For example, eight industrial beta-sites with intelligent process control capability (SMARTMolding system) have been established since January 2002. Figure 11 shows the current technology transition structure at UD-CCM, where industry partners benefit from technology advancements in the AMIPC program.

LOOKING FORWARD

The application of intelligent process control to multifunctional composite materials is key to meeting the needs of the Navy for 21st Century shipyards. Concurrent development of new materials and processes to meet demanding performance requirements of next generation ship systems will require the following:

- New materials capable of performing multiple functions.
- Rapid insertion of new technologies through concurrent development of design, materials, and processing to deliver performance that can be affordable.
- Intelligent processing to develop affordable processes for next generation multifunctional composite materials.
- New sensor technologies for inspection and health monitoring.

REFERENCES

S.G. Advani and M. Sozer "Process Modeling in Composite Manufacturing", Marcel Dekker, Inc., 270 Madison Ave., NY, NY 10016, (2002)

Department of Navy: Science and Technology Grand Challenges, http://www.onr.navy.mil/sci_tech/grandc.htm

A. Dominauskas, D. Heider, and J.W. Gillespie, Jr., *Electric Time-Domain Reflectometry Sensor For Online Flow Sensing In Liquid Composite Molding Processing,* Composites Part A, vol. 34(1), pp. 67-68 (2003)

A. Dominauskas, D. Heider, and J.W. Gillespie, Jr., TDR-Line Sensor for Multifunctional and Distributed Sensing in LCM. Proceedings of the 48th International SAMPE Symposium, pp. 290-302 (2003).

R.C. Don, K.R. Bernetich, B. K. Fink, M. Louderback, and J.W. Gillespie, Jr., "Large-Scale Implementation of Flow and Cure Sensing in a Thermoset Resin Infused Composite Structure," Proceedings of the 43rd International SAMPE Symposium, pp. 268-276 (1998)

B.K. Fink, J.W. Gillespie, Jr., E.F. Gillio, and K.R. Bernetich, "One-Step Resin Transfer Molding of Multifunctional Composites Consisting of Multiple Resins," US patent application, April 1997 (ref#08/956,595)

Future Naval Capabilities (FNC), http://www.onr.navy.mil/fncs/

B.K. Fink, S.H. McKnight, and J.W. Gillespie, Jr., "Co-Injection Resin Transfer Molding for Optimization of Integral Armor," Proceedings of the 21st Army Science Conference: Science and Technology for Army After Next, Norfolk, VA, June 15-17, 1998

B.K. Fink, S.M. Walsh, D.C. DeSchepper, R.L. McCullough, R. C. Don, B.J. Waibel, and J.W. Gillespie, Jr., *Advances in Resin Transfer Molding Flow Monitoring Using SMARTweave Sensors,* Proceedings of the ASME Materials Division, vol. 69-2, pp. 999-1015 (1995)

D. Heider and J. W. Gillespie, Jr., *Automated Processing of Large-Scale Composite Structures Using Smart-Molding,* to be published in the SAMPE Journal in 2004

J.M. Lawrence, K.T. Hsiao, R.C. Don, P. Šimáček, G. Estrada, E.M. Sozer, H.C. Stadtfeld, and S.G. Advani, *An Approach to Couple Mold Design and On-line Control to Manufacturing Complex Composite Parts by Resin Transfer Molding,* Composites Part A: Applied Science and Manufacturing, vol. 33(7), pp. 981-990 (2002)

T. Pike, M. McArthur, and D. Schade, Vacuum Assisted Resin Transfer Molding of a Layered Structural Laminate for Application on Ground Combat Vehicles, Proceedings of the 28th International SAMPE Technical Conference, pp. 374-380 (1996)

C.P. Ratcliffe and R.M. Crane, A Non-Destructive Test Procedure for the Determination of the Structural Irregularity and Damage Evaluation Routine (SIDER) of Composite Structures, Navy Case No. 83,356, August (2001)

C.P. Ratcliffe, *A Frequency and Curvature Based Experimental Method for Locating Damage in Structures.* ASME Journal of Vibrations and Acoustics, vol. 122(3), pp. 324-329 (2000)

P. Šimáček and S.G. Advani, Process Modeling and Simulation for Liquid Composite Molding, Proceedings of 34th SAMPE Conference, CA (2003)

P. Šimáček and S.G. Advani, LIMS 5.0 and LIMS UI User Manual, Tech. Report, CCM, University of Delaware, 2002

Technology for the United States Navy and Marine Corps, 2000-2035: Becoming a 21st-Century Force, Volume 6 Surface Platforms

Dr. Roger M. Crane is currently the Composite Materials Section Head in the Structures and Composites Department at the Carderock Division, Naval Surface Warfare Center. He received a BS and BA from Loyola College in Baltimore, MD; an MS from The Johns Hopkins University; and a PhD from the University of Delaware. Since joining the NSWC in 1980, Dr. Crane has conducted research on composite materials including material formulation, development of processing techniques, design and manufacturing of prototype applications, and development of nondestructive evaluation techniques. He has authored more than 75 technical publications and has 20 patents in composite technology.

Dr. Jack Gillespie has served the University of Delaware Center for Composite Materials (UD-CCM) in several roles for more than twenty years, achieving the position of Director in 1996. As an educator, Professor Gillespie has established an intellectually stimulating and highly interdisciplinary research environment for graduate and undergraduate students and post-doctoral candidates who work at UD-CCM. He has advised more than 60 graduate degree students who have gone on to successful careers in academia, government and industry. He was also chosen as the recipient of the Faculty Advisors Award from SAMPE in 2001.

Dr. Shridhar Yarlagadda has been conducting research on innovative processing and the manufacturing of composites over the past five years. As the Assistant Director of Research at the University of Delaware's Center for Composite Materials (UD-CCM), he works on several DOD-funded programs. Those programs include environmentally friendly processing, repair and remanufacture, high volume thermoplastic composite processing, resistive and magnetic susceptor design, process optimization, and smart temperature control based on the Curie temperature of magnetic nano-materials.

Dr. Suresh G. Advani is a Professor in the Mechanical Engineering Department and Associate Director of the Center for Composite Materials at the University of Delaware. He received his B Tech degree in mechanical engineering from IIT Bombay in 1982 and his PhD in mechanical engineering from the University of Illinois at Urbana-Champaign in 1987. His research interests are in rheology, fluid mechanics and heat transfer as applied to manufacturing processes, especially for polymers, nano composites and polymer composite processing. He has co-authored more than 200 journal and conference proceeding articles. Dr. Advani is a Fellow of the American Society of Mechanical Engineers and was recently appointed as the North American Editor for the journal *Composites A: Applied Science and Manufacturing.*

Dr. Dirk Heider is the Assistant Director of the University of Delaware Center for Composite Materials (UD-CCM). He received his PhD in electrical engineering from the University of Delaware in 1998 and holds the equivalent of BS and MS degrees from the Technical University of Aachen in Germany. Dr. Heider's research interests include advanced sensing methods and intelligent process control of composites manufacturing, and he has published more than thirty papers in these areas.