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MARINE TECHNOLOGY
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Mega Yachts

Designing for maximum loads

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The next-generation lifeboat

Marine Composites

Lowering weight, cost, and maintenance

IN PURSUIT OF HIGH PERFORMANCE

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Designed by John Shuttleworth Yacht Designs Ltd. and built by McConaghy Boats, the 42.5-m trimaran *Adastra* has a superstructure made of carbon fiber with Nomex honeycomb core, with the hull being glass/Kevlar foam sandwich. Photo courtesy John Shuttleworth Yacht Designs Ltd.



MARINE COMPOSITES

Reducing weight, cost, and maintenance in the maritime environment

By Eric Greene



Composites are defined as the combination of two or more materials that produce structural properties superior to the materials on their own.

This can be anything from mud and straw huts to concrete reinforced with rebar. However, we usually understand composites to mean fiber reinforcements combined with polymer resin matrix systems. Fifty years ago, marine composites were almost exclusively fiberglass, a combination of e-glass reinforcement and polyester resin. Today, high performance reinforcements, such as carbon fiber and Kevlar, are combined with advanced resin systems to produce very strong, lightweight structures that were not possible fifty years ago. Fortunately, design methodologies and manufacturing processes also have advanced, so everything from racing kayaks to destroyer deckhouses now is built with marine composites.

Recreational and commercial vessels

Fiberglass construction of recreational sail and powerboats really took off in the 1960s as builders realized they could manufacture multiple copies of the same design from a single mold. Complex shapes were easy to reproduce and the non-corroding fiberglass laminates were

marketed as virtually maintenance free. Widespread mass production made boating affordable to many Americans and the industry closely tracked the country's prosperity. Unfortunately, designs and manufacturing processes were developed by trial and error, which led to some boats that failed over time and some that would be considered "overbuilt" by today's standards.

Fiberglass construction was particularly attractive for the construction of commercial fishing boats, especially in the Pacific Northwest. However, the boom-bust cycle of local fisheries saw the boats lasting longer than the industry they supported. The durability of these boats was noticed by maritime law enforcement agencies and fiberglass patrol and utility boats became popular. Meanwhile, lightweight composite construction was evolving overseas to support the high-speed ferry market.

Military applications

The United States Navy has actually been using composite materials since the 1950s to satisfy demanding fleet

requirements. Composite submarine bow domes, which can weigh more than 43,000 pounds, have been used since the mid-50s because sonar waves can travel through the material. Submarines have also used composite fairings around periscope masts for about as long because composites can be easily molded to an airfoil shape and are non-corroding. The navy also built a dozen all-fiberglass minehunting ships in the 1990s. At the time, these 188-ft ships were the largest composite vessels ever built. Their monocoque, frameless construction was non-magnetic and designed to resist shock loading from undersea explosions. Composites were the only materials that could meet the navy's mission requirements for these applications. Other applications also have survived rigorous qualification testing before they could prove their value to the fleet.

The navy's primary marine composites research over the last two decades has been with the goal of producing a deckhouse structure that improves stealth and reduces topside weight and maintenance. The navy took a stepping stone approach that culminated in the all-composite DDG 1000 deckhouse that is an integral feature of the new Zumwalt-class destroyer. The navy's research lab in

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Bethesda, Maryland (NCWCCD) worked with the nation's biggest defense contractors and small subcontractors to solve design, manufacturing, and damage tolerance issues by building a series of technology demonstrators. Some of these, including a weapon director room, a helicopter hanger, and a destroyer rudder, underwent full-scale testing (such as shock, blast, and fire) but were never fielded on ships. In contrast, the Advanced Enclosed Mast system was fielded on a test ship before becoming a part of the LPD-17 baseline design. Some concepts, such as a composite "island" for aircraft carriers never made it past paper studies, yet all contributed through analysis and component testing to the confidence required to build the DDG 1000 deckhouse.

Sandwich construction

Early fiberglass boats were made using solid laminates where successive plies of reinforcement were wet out with resin by hand and placed in a mold. In the 1970s,

lightweight cores were introduced to create sandwich structures that behaved like I-beams, with the cores primarily transmitting shear loads. Sandwich panel structures that resisted out-of-plane hydrostatic and hydrodynamic loads could be made much lighter than solid laminates.

Today, almost all high-performance marine laminates use sandwich construction. Early sandwich construction presented manufacturing challenges to ensure a good bond to the skins and also introduced additional potential failure modes, such as core shear, skin-to-core bond failures, and water intrusion into the core. Today's designs have solved most of these problems, but marine surveyors remain active in tracking issues on some early cored-construction boats.

Material development

Composite materials fall into three major categories: reinforcement, resin, and cores. Each type of material has seen major developments over the last fifty years, which have increased laminate performance. Originally, e-glass was the reinforcement used overwhelmingly by the boatbuilding industry. Carbon fiber has higher strength than e-glass and, more importantly, much higher stiffness. Kevlar has a density less than water with high tensile strength and toughness. In addition to the use of new fiber came the introduction of new fiber architectures beyond the traditional woven roving or mats. Knits and unidirectionals stitch or bond fibers together rather than weaving them, which creates much better in-plane properties that are useful with sandwich construction.

Resin systems hold the reinforcements together and transmit loads between the plies so it is of little value to improve reinforcements without improving resins. Thermoset resins (liquid polymers that cure into solids by cross-linking molecules) have evolved from polyester to vinyl ester and epoxy, with increasing strength and strain to failure values. Vinyl esters and epoxies also have superior secondary bond and hydrolytic resistance characteristics when compared to polyester resin.

End-grain balsa wood was one of the earliest core materials used because it has very good shear properties for its weight and indeed is still widely used today. Foam cores were developed that are even lighter and could be tailored to optimize dynamic performance. For extremely lightweight, high performance sandwich structures, racing boats now use honeycomb cores that are common in the aerospace industry.

Manufacturing process improvement

Early fiberglass boatbuilders realized that they could create a very accurate female mold once and then reproduce the shape with relative ease by hand laminating into the mold.

At approximately 900 tons (outfitted), the DDG 1000 destroyer deckhouse, an integral feature of the new Zumwalt-class destroyer, is claimed to be the largest composite structure ever built. Photo courtesy Huntington Ingalls Industries, Inc.



This process usually involves buckets of catalyzed resin that are used to wet out the reinforcement while operating under a time window before the resin hardens. Brushes and rollers are used to apply the resin and special ribbed rollers are used to consolidate the laminate and remove air bubbles. The quality of the laminate is very dependent on the skill of the laminator and workers are exposed to volatile organic compounds (VOCs) present in the styrene-base resin system, which are suspected to be carcinogenic.

Some builders realized that a vacuum bag placed over the laminate would help to consolidate it, especially when trying to bond cores in place. In 1990, Bill Seemann took the process one step further by placing the vacuum bag over a dry stack of reinforcement and using the vacuum to pull resin into the laminate. His biggest challenge was to keep the laminate from sealing itself off under vacuum so he invented what today we call “flow media” to distribute the resin. He dubbed the technique the Seemann Composite Resin Infusion Process or SCRIMP, which today has evolved generically into resin infusion. Laminates produced using this method have uniform thickness, high fiber and low void contents, and do not expose workers to VOCs.

The aerospace industry requires even lighter, high-performance laminates in smaller quantities than boats or ships. They typically use reinforcements that are pre-impregnated with partially cured resin, or prepregs. The prepregs are transported and stored in freezers to maintain the state of partial cure; heat is applied only after the prepregs are placed in the mold and consolidated under vacuum. The consolidation or “debulking” process often has to be done in stages, adding additional labor costs. Prepreg construction is used for high-performance racing boats but is not practical for marine applications with very large surface areas.

Early fiberglass boat construction was truly like taking a time machine trip back to the Wild West. Some people

made a lot of money and a lot of great discoveries were being made but the rule of law, or design guidelines, was missing. The term “best practices” had yet to be invented, which contributed to the boom or bust mentality. Often spurred by material suppliers or end-users, the marine composites industry silenced early critics by systematically addressing design, manufacturing, and in-service performance issues.

Design tool development

The first fiberglass boats were designed using a trail-and-error methodology, which led to some early failures; but more often, it resulted in boats that were built heavier than necessary. This was not always a bad thing, as boaters find ways to land themselves on the rocks or otherwise push their vessels beyond their intended service. Without the fifty years of hindsight we now have, nobody truly knew how long these structures would last. Indeed, one of my favorite anecdotes about my dad’s first fiberglass boat, a Block Island 40, has its designer, William Tripp Jr., repeatedly driving over a test panel with the family car to prove how tough the hull would be. It must have worked, because I just saw the boat listed for sale 55 years after she was built (at six times what my dad paid for her).

In 1960, Gibbs & Cox produced the *Marine Design Manual for Fiberglass Reinforced Plastics*, which provided insight on how fiberglass materials of the day performed as boat structure. Design details and laminate properties were presented via graphs and tables and this served as the primary design resource until the American Bureau of Shipping codified its *Rules for Building and Classing Reinforced Plastic Vessels* in 1978. These prescriptive rules for plating thickness and scantling sizing produced designs that would be considered conservative by today’s standards.

Classical laminate theory (CLT) considers laminates as plies with unique strength and stiffness characteristics that



The *Seabreacher X* can sustain high-speed dives and then breach the surface, launching the entire vessel clear out of the water. The unique personal watercraft uses a hand-laid composite, monocoque structure built by Rob Innes and Dan Piazza of Innespace Productions in New Zealand.

are analyzed using matrix algebra. Analysis of composite laminates using CLT grew popular as personal computers became more common in the 1980s. CLT still forms the basis of most laminate analysis software today but generally only considers panel structures.

Finite element analysis (FEA) for complex marine structures is an accepted tool to determine stress levels and areas of stress concentration that require design refinement. Using FEA for composites highlights the need to move from 2D shell elements to 3D layered solid elements. As-built ply stiffness and strength characteristics need to be known in a 3-axis system, and details such as joints and ply drop-offs need to be modeled with sufficient fidelity.

Because composites are non-homogeneous, layered structures, failure cannot always be accurately predicted using linear FEA methods. Current state-of-the-art proposes the use of multicontinuum theory (MCT) algorithms to decompose lamina (ply) stress/strain fields down to the fiber and matrix (resin) level. This level of detail is suitable for a relatively simple structure, such as a bicycle frame, that will be manufactured in quantity. High performance structures engineered on the edge of catastrophic failure, such as America's Cup yachts, also warrant this detailed FEA approach. However, the design of geometrically complex marine structures for everyday use may not warrant complex models with billions of elements that may need to be run on supercomputers.

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A move towards standard manufacturing, joining, and detail designs will help to ensure the validity of even the more basic finite element models. A key element here is verification that as-built marine structures behave as predicted, which can only be confirmed with full-scale testing and at-sea experience.

Process control

Process control for marine composites manufacturing took a quantum leap forward with the advent of resin infusion. The process produces laminates with very predictable fiber-to-resin ratios and virtually no voids. Gone are the days when a worker may have applied too much resin in one area or too little in parts of the mold that were difficult to access. However, resin infusion is not infallible: Air leaks in the vacuum bag can introduce voids; corner details can create bridging or reinforcement wrinkling; and the working time of resin before it cures may be too short to wet-out the entire part. Trained quality assurance (QA) personnel can detect most of these problems before the actual infusion takes place, which is more realistic than having a QA person continuously looking over the shoulder of a laminator during hand layup operations.



Many builders are fabricating large, flat panels on laminating tables and then joining them to create ship modules. The flat panels can be produced with enhanced levels of process control, including layout with overhead laser systems and 100% ultrasonic non-destructive evaluation (NDE).

As much as marine composite construction is refined and automated, there is no getting around the fact that unlike metallic structures, the plating material itself is being created on the shop floor. Therefore, representative test laminates must be evaluated to ensure the anticipated mechanical properties are achieved. Visual inspection and advanced NDE techniques are critical in areas of high stress concentration, which are often highlighted in FEA models.

Environmental and health issues

As noted earlier, resin infusion is a closed mold process that virtually eliminates worker exposure to VOCs. Secondary bonding used to join panels together may be done using hand layup techniques, in which case respirators with an independent air supply should be used. Dust from trimming operations is best collected at the source using tools equipped with vacuum pick-up hoses.

Society is increasingly concerned with end-of-life issues associated with large marine structures. Experience has shown that composite boats survive longer than their



machinery and outfit, creating a big demand to renovate older, classic designs. Unlike metals, composites cannot be easily recycled for reuse and today the most promising technology involves grinders that reduce unwanted composites into structural fillers for reuse. With the proliferation of composite wind turbine blades that will reach the end of their useful life in a few decades, we can expect new, innovative composites recycling methods to emerge.

Composite structures (especially sandwich laminates) have a lot more types of potential failure mechanisms than traditional metallic structures. And because composites are layered, damage is not always apparent using only visual inspection. A recent Ship Structure Committee report (which can be found at www.shipstructure.org/pdf/463.pdf) cataloged defects and damage found in marine composites and the suitability of various NDE techniques for detecting the flaws. The report concluded: "By far and away, the best NDE tool for marine composites is still the human eye. Coupled with an experienced surveyor who understands how composite structures resist loads in a marine environment, damage is most often first detected through visual inspection. However, visual inspection cannot reveal the extent of damage with certainty. Defects or damage can exist deep within layers of a laminate, which may not be detected by looking at the surface. Sandwich laminates have additional failure modes that require advanced NDE methods, such as core failures and bondline deficiencies. The initial assessment of NDE technologies revealed laser shearography, thermography, ultrasonic testing and digital tap hammers to be the most promising for marine composites inspection."

Repair

Depending on the size of the failure, most repairs to marine composite structures can be accomplished with a minimum of specialized equipment and worker training. The primary objective is to achieve a good secondary bond from the repair resin system. This requires good surface preparation, adequate repair taper, and optimal laminating conditions. It is always desirable to replace damaged material with similar products. It may seem intuitive to make the

The *Turanor PlanetSolar* is a 31 m wavepiercer catamaran with approximately 537 m² of solar panels on its deck that drive carbon fiber propellers. Designer Craig Loomes from New Zealand specified advanced carbon fiber hull construction, and the boat completed a circumnavigation voyage in May 2012. Photo courtesy PlanetSolar SA.

TOP: The Wave Star Energy marine hydrokinetic energy concept was invented by sailing enthusiasts Niels and Keld Hansen in 2000. The half-submerged buoys rise and fall, allowing energy to be continually produced despite waves being periodic. The buoyancy of the float is 20-40 times its dry weight, made possible by composite construction. Photo by Eric Greene.

BOTTOM: The *Skjold* is a littoral combat craft built by Umoe Mandal in Norway between 1999 and 2006. She has an air-cushioned catamaran hull (surface effect) that relies on lightweight construction for high speed and maneuverability. Photo by Eric Greene.

repair stronger than the original to avoid future failures, but this can sometimes create a stress concentration if the cause of the failure is not first determined.

Major damage to areas of complex geometry can be repaired by molding a replacement section and bonding it in place using scarf joints. In boat hulls where the core of sandwich laminates has been compromised by water intrusion, the outer skin and damaged core can be removed and replaced.

Organic resin systems used in composites will support combustion if exposed to a high enough heat flux. Unprotected marine composite structure cannot meet the non-combustibility standard established for steel ships. However, sandwich composite structures are excellent insulators, which has proved to isolate large fires to a single ship compartment. In the wake of a fire on a composite Norwegian minesweeper in 2002 that resulted in a total loss, fire protection guidelines in the International Marine Organization (IMO) High Speed Craft code have

been adopted to ensure that fires are contained and don't spread on composite high-speed craft.

The United States Navy spent more than a decade testing the performance of composite structures in fires and developing fire protection guidelines before building the DDG 1000 deckhouse. Indeed, these fire protected marine composite structures retain their structural integrity better than unprotected steel in long-duration hydrocarbon pool fires.

Blisters occur to the underwater portion of fiberglass boats when water that has penetrated the outer layer of the laminate mixes with water-soluble materials to create an acidic fluid, which can attack the resin matrix or resin/fiber bond. The acidic solution attracts additional water via osmosis, which can create a blister or what is known as osmotic blistering. The primary causes of blistering are improper resin handling or contaminants that leave water-soluble material in the laminate and an insufficient barrier layer to keep moisture out. Since the problem first became apparent in the 1980s, builders have improved QA methods to eliminate water-soluble material and have adopted more water-resistant resin systems, such as vinyl ester or epoxy, for at least the outer laminate layers. Although osmotic blisters rarely compromise a hull's overall structural integrity, detection and repair of blisters in older boats remains a challenge for the industry.

Meeting today's needs

We've shown how far marine composites have come in the last fifty years, as well as some of the engineering challenges that have been overcome. The industry has been driven by the recreational boating market and high-performance innovation tends to germinate with competitive race boats. Design tools, manufacturing processes, and at-sea experience has matured to the point where marine composites are poised to enjoy an increased maritime market share and the United States has the expertise to benefit from it.

High performance boats

Recreational boaters and law enforcement officials will always strive to go faster in their boats and lightweight, composite construction makes this possible, while at the same time mitigating shock loads felt by the boat's occupants. Another trend we are seeing is the desire to minimize fuel consumption, both to reduce operating costs and to minimize environmental impact. Trimarans such as the John Shuttleworth-designed *Adastra* illustrate how lightweight construction is used to create innovative, very low resistance hull forms.

The military and scientific communities are very interested in exploiting the capabilities of unmanned surface and





Despite having sank in 2010 following a collision with another vessel, *Earthrace* holds the record for a powerboat to circumnavigate the globe at just under 61 days, running on 100% biofuel. Built in Auckland, New Zealand, by Calibre Boats, the hull was made from sandwich composites using 40 mm of PVC foam core sandwiched between three layers of carbon inside and out, with a layer of Kevlar for impact resistance on the outside. Photo by Eric Greene.

underwater vehicles. Maximizing endurance of these types of craft is always a goal and most prototypes to date use composites to create lightweight, hydrodynamic hull forms.

The SOLAS Convention and the United States Coast Guard require that ship structure be non-combustible, but Scandinavian shipyards, the United States Navy, and the IMO High-Speed Craft Code have shown through full-scale testing that equivalent levels of fire safety can be achieved with composite construction that uses structural fire protection. Composite superstructures not only reduce overall ship weight but also improve stability.

Trimarans such as the John Shuttleworth-designed *Adastral* illustrate how lightweight construction is used to create innovative, very low resistance hull forms.

The National Academy of Sciences recently released a report titled "Application of Lightweighting Technology to Military Vehicles, Vessels, and Aircraft." One of the conclusions in the chapter dealing with maritime platforms was that the U.S. needs to take advantage of its ability to build lightweight, high-speed ferries in order to further the development and reduce the cost of littoral combat ships.

Devices that extract kinetic energy from the ocean, such as wave buoys and tidal turbines, are ideally suited for composite construction. The ability to create complex structures that won't corrode in an ocean environment expands the design palette for this emerging field. Wind turbine blades now measure up to 75 m long and there is talk of 100-m blades for offshore wind platforms. The ability of these composite

structures to resist fatigue loading in a maritime environment will pave the way for devices placed in the ocean.

Reducing maintenance and manufacturing costs

Studies have shown that the annual cost of corrosion to the Department of Defense is more than \$20 billion, or 20% of available maintenance budgets. With that in mind, the United States Navy has qualified many composite components for shipboard use that may not be sexy but do indeed keep the fleet in a better state of readiness with less demand from the ship's force. Applications include pumps, deck drains, gratings, ladders, ventilation ducts and screens, and stanchions.

The navy intends to man its new littoral combat ships with a crew of 40. You will not see sailors on watch chipping rust and doing paint touch up, which is common on larger navy ships. Structure and outfit needs to be adapted to this environment—both non-corroding and lighter, so one person can do maintenance where it used to take two.

Commercial ship owners are also beginning to consider total cost of ownership, which can often offset higher acquisition costs associated with composite construction.

Many of the exciting applications of marine composites examined here are one-offs, or prototypes, where design considerations were not always cost driven. The true value of composites is realized on the factory floor when numerous copies of the same structure are produced from molds. Computer-aided manufacturing is used in composites fabrication in everything from multi-axis routers to create molds, to robots for finishing operations. Large composite structures can be built on-site, thus eliminating factory infrastructure and transportation costs. **MT**

Eric Greene founded *Eric Greene Associates, Inc.* in 1987 to focus on marine composites.