The Promise of Marine Composites Realized

Fifty Years of Marine Composites

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 but today 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 have also advanced so everything from racing kayaks to destroyer deckhouses is now built with marine composites.

Recreational Boats

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.

Commercial Vessels

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 U.S. Navy has actually been using composite materials since the 1950s to satisfy demanding fleet requirements. Composites submarine bow domes, which can weigh over 43,000 pounds, have been used since the mid fifties 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-foot ships were the largest composite vessels ever built. Their monocoque, frameless construction was non-magnetic and designed to resist shock loading from undersea explosions (UNDEX). Composites were the only materials that could meet the Navy's mission requirements for these applications. Other applications have also 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 (see Figure 3) that is an integral feature of the new Zumwalt-class destroyer. The Navy's research lab in 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 underwent full-scale testing (such as shock, blast and fire) but were never fielded on ships, including a weapon director room, a helicopter hanger and a destroyer rudder. 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 utilize 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 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 that has 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 is 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. 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 Manufacturing 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.

Challenges Met

Early fiberglass boat construction was truly like a trip to the Wild West in the early 1800’s. Some people made a lot of money and a lot of great discoveries were being made but the “rule of law” or design guidelines were 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 trial-and-error methodology, which led to some early failures but more often 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 noticed 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 are analyzed using matrix algebra. Analysis of composite laminates using CLT grew popular as personal computers became more ubiquitous 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.

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. Qualified 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 (see DDG 1000 and Skjold Figure xxs). 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 & Worker 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 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.

Non-Destructive Evaluation

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 (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 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.

Performance in Fires

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 proven 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 IMO High Speed Craft code have been adopted to ensure that fires are contained and don't spread on composite high-speed craft.

The U.S. Navy spent over 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.

Blistering
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 know 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. A trio of trimarans (see Figures xx – one is actually a catamaran with a center hull for extreme waves) 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 underwater vehicles. Maximizing endurance of these types of craft is always a goal and most prototypes to date utilize composites to create lightweight, hydrodynamic hull forms.

Ship Lightweighting
The SOLAS Convention and the USCG require that ship structure be "non-combustible" but Scandinavian shipyards, the U.S 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 utilizes structural fire protection. Composite superstructures not only reduce overall ship weight but also improve stability.

The National Academy of Sciences (www.nap.edu) 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 our ability to build lightweight, high-speed ferries in order to further the development and reduce the cost of littoral combat ships.

Hydrokinetic Energy Devices
Devices that extract kinetic energy from the ocean, such as wave buoys and tidal turbines, are ideally suited for composite construction (see Figure xx). 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 meters long and there is talk of 100-meter 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.

Maintenance Reduction
Studies have shown that the annual cost of corrosion to the Department of Defense is over $20 billion, or 20% of available maintenance budgets. With that in mind, the U.S. 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 & screens, and stanchions.

The Navy intends to man its new littoral combat ships with a crew of forty. 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.

Reduced Production Manufacturing Costs
Many of the exciting applications of marine composites cited in this article 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.

Our oceans are truly the next frontier and marine composites are up for the challenge.

Eric Greene Bio
Eric Greene received his S.B. in Naval Architecture and Marine Engineering from the Massachusetts Institute of Technology in 1979. Mr. Greene founded Eric Greene Associates, Inc. in 1987 to focus on marine composites. He has served as principal investigator for five Ship Structure Committee projects. Mr. Greene has written for Professional BoatBuilder and Composites Fabricator Magazines and is a regular presenter at the International BoatBuilder's Exhibition conference.

Figure 1. The 42.5-meter trimaran *Adastra* was recently launched in China. She was designed for exceptionally low fuel consumption, excellent sea keeping qualities and luxurious accommodation. Extensive structural analysis was conducted to account for side slamming, wave impact, and torsional effects of the outrigger riding through waves. The superstructure is carbon fiber with Nomex® honeycomb core, the hull is glass/Kevlar® foam sandwich and the interior is light weight oak cabinetry using honeycomb panels. To help reduce weight, virtually every aspect of the boat is custom built. This includes carbon fiber hatches, portlights, ladders and even hinges, which are all built specifically for the vessel.

photo credit: www.john-shuttleworth.com

Figure 2. Three and a half years after being launched in August 2008 and after her second attempt, the Maxi *Banque Populaire V* has wonthe Jules Verne Trophy with a circumnavigation that took just over 45 ½ days.   Loïck Peyron and his crew covered 29,002 miles at an average speed of 26.51 knots. The 40-meter trimaran was built by CDK Technologies in the Brest region of France using advance composite materials.

photo credit: www.voile.banquepopulaire.fr/press/Maxi-Trimaran-Banque-Populaire-V

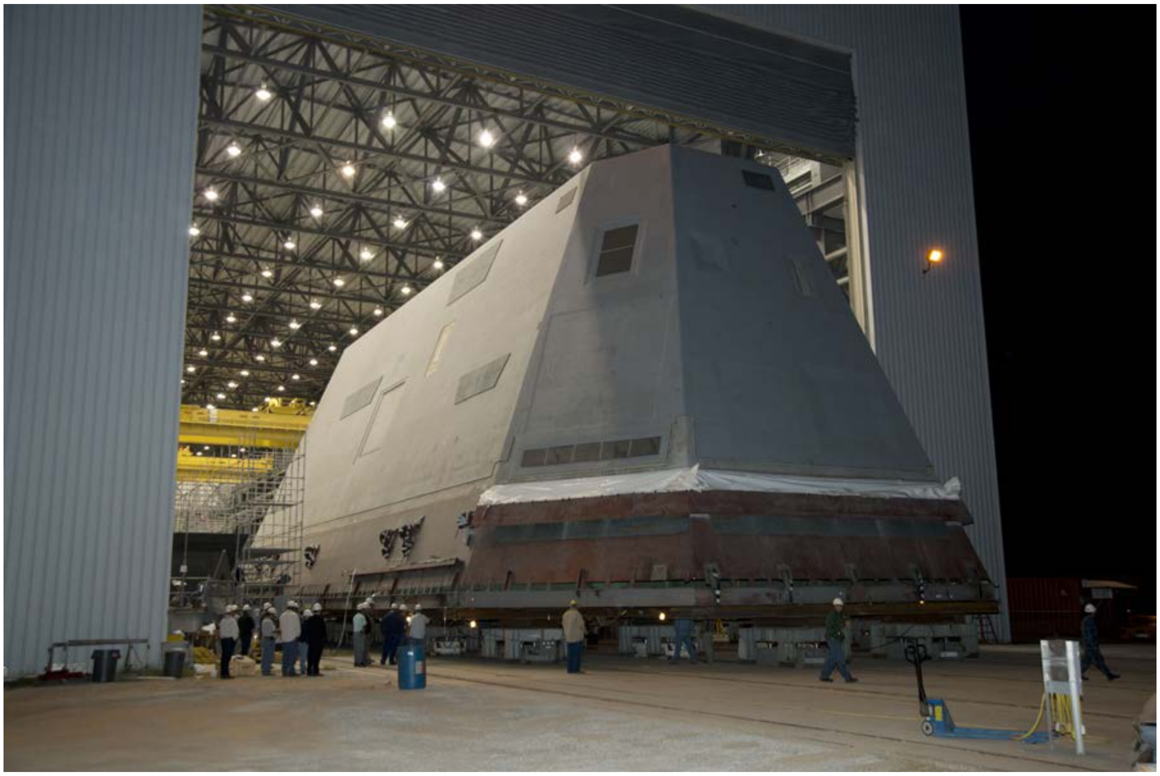

Figure 3. At about 900 tons (outfitted), the DDG 1000 destroyer deckhouse is claimed to be the largest composite structure ever built. To reduce radar cross-section, ship antennas (apertures) are embedded directly in the structure itself. Huntington Ingalls Industries claims they can build panels up to 150 by 50 feet and assemble large structures to a tolerance of less than 1/8th of an inch.

photo credit: Huntington Ingalls Industries

Figure 4. *Earthrace* holds the record for a powerboat to circumnavigate the globe at just under 61 days. The boat was run on 100% biofuel, claiming a net carbon zero footprint in order to draw attention to the need for renewable fuels and sustainable living. *Earthrace* was built in Auckland, New Zealand, by Calibre Boats, who specialize in high-tech composite boatbuilding. The hull is made from sandwich composites using 40mm of PVC foam core sandwiched between three layers of carbon inside and out, with a layer of Kevlar® for impact resistance on the outside (albeit, insufficient to resist being rammed by a Japanese whaling vessel during a confrontation in 2010).

photo credit: Eric Greene

Figure 5. movistar was built to the Volvo Open 70 rule for the 2005-6 Volvo Ocean race. She is pictured here sailing down the Chesapeake Bay on way to New York. The boat sank on the next leg of the trip to Portsmouth, UK after her aft keel bearing collapsed and broke away from the hull allowing water to pour into the hull. The boat was built by the Australian yard Boatspeed using 70°C cure prepregs and Corecell™ foam core from SP Systems (now Gurit).

photo credit: Eric Greene

Figure 6. The *Turanor PlanetSolar*, is a 31meter wavepiercer catamaran with approximately 537 square meters of solar panels on its deck that drive highly efficient carbon fiber propellers. Designer Craig Loomes from New Zealand specified advanced carbon fiber hull construction to achieve a 65,000 kg displacement. The boat was completed by the Kiel, Germany yard of Knierim Yachtbau in 2010 and completed a circumnavigation voyage in May 2012.

photo credit: www.planetsolar.org

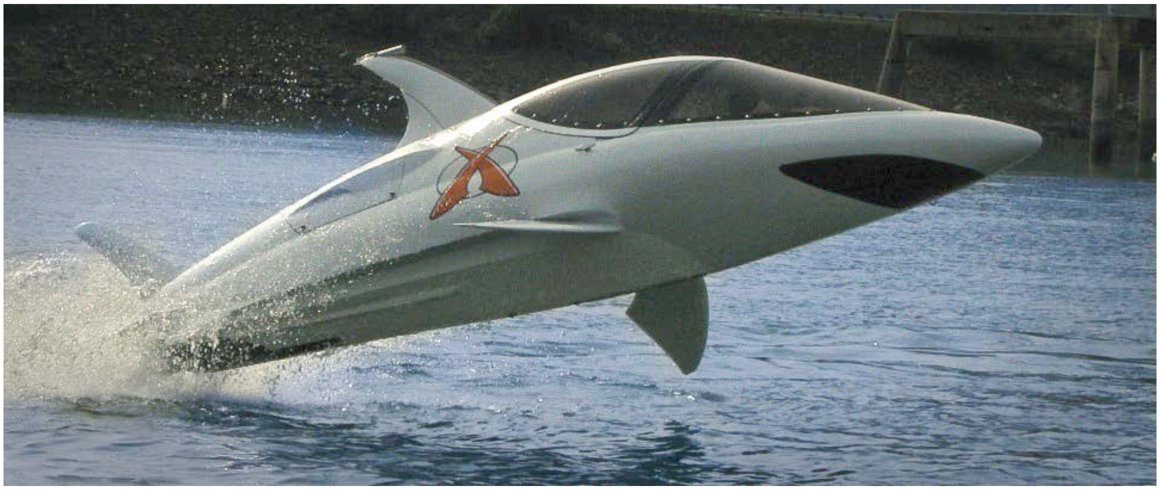

Figure 7. The *Seabreacher X* can sustain high speed dives and then breach the surface, launching the entire vessel clear out of the water. The new fully vectored thrust system mimics the tail articulation of real aquatic animals like sharks and dolphins. This unique personal watercraft utilizes a hand-laid composite, monocoque structure built by Rob Innes and Dan Piazza of Innespace Productions in New Zealand.

photo credit: www.seabreacher.com

Figure 8. The *Skjold* is a Littoral Combat Craft (LCC) built by Umoe Mandal in Norway between 1999 through 2006. She has an air-cushioned catamaran hull (surface effect) that relies on lightweight construction for high speed and maneuverability. The ship utilizes flat panels built on a laminating table and joined using secondary bonding methods.

photo credit: Eric Greene

Figure 9. The *Vestas Sailrocket 2* has smashed its own world speed sailing record after hitting 65.45 knots (121.21 km/h) over 500 meters, in Walvis Bay, Namibia. The boat was designed and built by the Sailrocket team in the VESTAS R+D facilities in East Cowes on the Isle of Wight. The build took 16 months.

The main structure is made from SP GURIT pre impregnated carbon fiber with a Nomex® honeycomb core. The main foil was constructed by Composite Craft around a carbon fiber spar and cured in Green Marine's autoclaves. The wing skins are a polyester heat shrink film.

photo credit: www.sailrocket.com

Figure 10. 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 credit: Eric Greene

Figure 11. *Solution* is a 43-meter Global Response Cutter designed for littoral & offshore security and patrol. She was built by Westport Shipyard, which was founded in 1964 and is considered a pioneer in the use of composite materials in the boat building industry. They claim composite construction delivers exceptional structural integrity that meets or exceeds ABS strength rules while providing greater speed / longer range and reduced fuel burn; offers superior noise and vibration reduction; delivers superior cooling and heating benefits; reduces heat, radar, acoustic, and magnetic signature; and does not rust/corrode, thus reducing life cycle costs.

photo credit: Eric Greene