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SMART MANDRELS ENABLE NASA CRYOTANK

MARCH 2016

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Source / NASA

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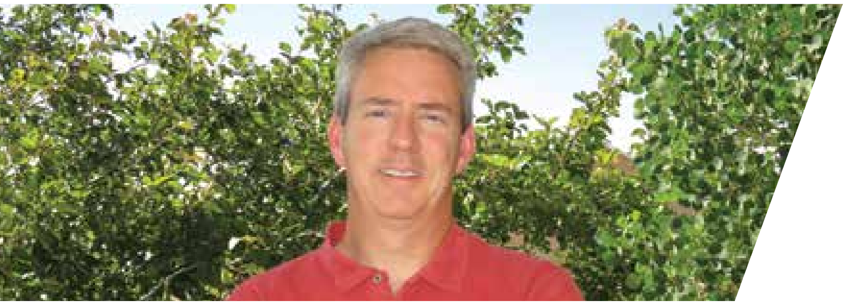

The challenge of reliable NDE for aerocomposites

I was on a flight recently and struck up a conversation with the man seated next to me. As we asked and answered the usual questions ("Where are you going?" "What do you do?"), I learned that he does oil and gas pipeline rehabilitation and maintenance. This, as you might guess, makes him a busy man, particularly in an industry where the transport of product (oil and gas) is money earned, and where lack of transport is money lost. (For a fuller understanding, Google "U.S. oil and gas pipeline map" and you'll see how complex and vast the challenge is.)

Anyhow, my new friend, it turns out, knows a little bit about advanced materials in general, including composites, and we got to talking about the carbon fiber composites used in the Boeing 787 and the Airbus A350 XWB aircraft. He had a lot of questions for me about where composites are used and how. And then he asked what would appear to be a simple question: "How are composites on an airplane repaired?"

"Ah. Well," I said, stroking my chin sagely, "repairing a composite material can be tricky, but it's very doable. The real question is how do you know if it is damaged at all?"

One advantage of an aircraft fabricated from aluminum or titanium is that damage, in the form of a dent, crack or corrosion, usually can be detected via simple visual inspection. Barring this, there is well-established nondestructive evaluation (NDE) technology available to help technicians find and assess sub-surface cracks, thinning and corrosion. Much of the NDE technology used relies on aluminum's and titanium's conductivity, which enables the use of electrical signaling.

Aerospace composites offer well-documented advantages compared to aluminum and titanium, not the least of which is their ability to resist corrosion. Composites are also remarkably dent-resistant. But it is in the nature of their complex, layered composition to experience internal cracking and delamination, sometimes long before that damage becomes apparent on the part surface. That seriously limits the value of visual inspection. Further, although composites have been used in aircraft substructures for many years, there is not an established NDE regime in place to help maintenance personnel assess subsurface damage. This does not mean that there is *no* NDE technology available to check a composites structure for damage. Far from it. The NDE technology selection is vast, ranging from traditional C-scan to ultrasonic to adaptive beam forming to radio frequency to microwave. And more. On top of that, the user interface for each of these also varies, ranging from handheld units to larger freestanding or surface-mounted systems.

Even more problematic is the question of what to do with the gathered data. Many NDE systems currently on the market generate images and/or information that must be assessed by someone trained to interpret the results and able to recommend an appropriate course of action.

What we know is that Boeing, Airbus and the airlines to which they've sold 787s an A350 XWBs are in the midst of figuring out which NDE technologies are most accurate and efficient, particularly for technicians and maintenance personnel in the field who are, in some cases, coming face-to-face with composites for the very first time and are on the front lines of damage assessment. This is not a trivial challenge — the relative newness of aerocomposites means that the performance of aircraft maintenance, repair and overhaul organizations (MROs) will face extraordinary scrutiny, and reliable NDE will be a necessary validation tool.

Ideally, NDE of an aerocomposite will involve a simple, robust handheld device that quickly generates easily understood results that help maintenance personnel make quick decisions regarding repair requirements. Such technology is not here yet, but it is close, and the next few years should prove revelatory.

CW will continue to track this technology for you, as well as the related issue of aircraft repair itself. Look for a full report on current commercial repair strategies next month in the April issue of *CW*.

JEFF SLOAN — Editor-In-Chief

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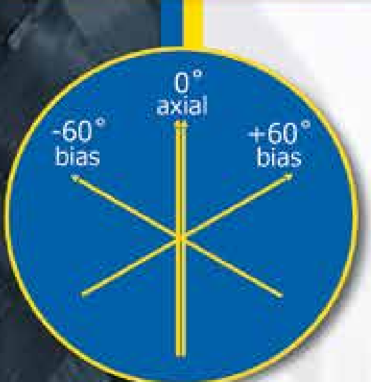

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“Give us affordable carbon fiber!”

» The market for carbon fiber has doubled in a decade but customers continue to say it’s too expensive. Having been a producer of carbon fiber — I count myself in that category, given my extensive experience in starting up and commissioning carbon fiber lines — I know we have the ability to influence the market’s future growth, keeping in mind that market segments are sending different messages, based on different needs.

In the aerospace and high-end sporting goods sectors, performance is the key, and customers will pay for that performance. In the industrial segment, however, which includes energy and automotive, the message is, “We want carbon, and a lot of it, but we don’t want to pay more than €10/kg.” Wind blade producers certainly recognize that carbon fiber can reduce total system cost. If blades can be made lighter, then other components can be made lighter as well, including the gearbox, tower and foundation, for a lower total system cost. Automakers, on the other hand, haven’t forgotten the “$5/lb” message originally put forth by Zsolt Rumy of Zoltek Corp. (St. Louis, MO, US) in the late 1990s. Further, automakers say they want “kilos today, kilos tomorrow, and 10,000 MT in five years.” How can we meet such expectations?

> We need a sustained, cooperative effort in the carbon fiber supply chain. Partnering is the key.

I believe we can do it by examining all the opportunities in the carbon fiber value chain closely. First, world oil production is currently around 27 billion barrels per year. That breaks down to about 90 million MT of propylene per year and 7 million MT/yr of acrylonitrile. From there, about 2 million MT goes into acrylic fiber production, of which a small percentage is made into the polyacrylonitrile (PAN) precursor that subsequently becomes from 50,000 to 75,000 MT of carbon fiber today. That’s a very *small* amount compared to the enormous volume of upstream oil production — in other words, our industry has *no* influence on raw material cost.

So what other aspects of the supply chain can we affect? PAN precursor accounts for the largest chunk of carbon fiber cost. Each producer pays roughly the same price for acrylonitrile, but its cost of PAN precursor can differ depending on infrastructure, scale, labor and utilities costs. The same situation exists for carbonization cost, where conversion ratios are roughly the same but there are some significant differences in scale and infrastructure, and regional differences in utilities and labor costs.

Overall, the cost of carbon fiber dropped — a lot — since the 1980s, and then leveled off after 2000, despite the fact that raw material cost has moved up and down with the price of oil. I believe the price drop was a function of the industry scaling up and each producer becoming more efficient. Additional carbon fiber cost reductions of 10-20% or more could come from further *incremental* improvements and/or efficiencies in equipment, scale, labor and energy use. Volume is your friend in carbon fiber: The considerable investment necessary to scale up capacity can be raised with strong development partners and long-term customer supply agreements. Incremental cost savings can be realized by improving delivery options, using a lower-cost finish oil, running a single fiber product, optimizing sizings and employing automation where practical in new lines to reduce touch labor.

In the automotive sector, we also can reduce the cost of carbon fiber intermediates, that is, prepregs and woven fabrics, by improving material purchasing efficiencies, using the right process to make the product, and, perhaps most importantly, increasing conversion rates to minimize waste.

The reality is that regardless of carbon fiber cost, converting it and producing auto parts is rather expensive. Using resin transfer molding (RTM), for example, is certainly an advantage over hand laid, autoclave-cured prepreg. I believe that the cost of making a carbon fiber auto part — today, in the range of €85/kg (US$92/kg) — will be reduced by 70% or more through better part design, automated near-net processing at an optimized scale, fewer processing steps and consumables, and lower-cost resins. Winning processes likely will include high-pressure RTM and compression molding systems optimized for part types (structural, semi-structural or Class A surface). These have the potential to deliver high-volume serial production parts at a cost of €20-€25/kg (US$23-US$28/kg).

To make this happen, we need a sustained, cooperative effort among carbon fiber producers, resin suppliers, equipment designers and manufacturers, automation experts *and* automotive OEMs. Partnering is the key, and from our end — the carbon fiber suppliers and the composites industry — we need to produce consistent fiber supply and continue to optimize processes to achieve high-quality, repeatable parts in short cycle times. We *can* make PAN carbon fiber, and carbon fiber parts, affordable. CW

ABOUT THE AUTHOR

Daniel Pichler is joint managing director and project leader at CarbConsult GmbH (Hofheim am Taunus, Germany), a consultancy that serves clients in the carbon fiber manufacturing and composites and chemicals industries, and other interested parties, in Europe, the US and Asia. He has more than 30 years’ experience with carbon fiber, composite materials and other high-performance materials and components. Pichler previously led SGL Group’s (Wiesbaden, Germany) carbon fiber business (1999-2008) and oversaw the startup of Aksa’s (Istanbul, Turkey) carbon fiber business (2009-2012) as well as HCC’s (Moscow, Russia) Alabuga international business-development efforts from 2012 through mid-2015.

IACMI – One insider's perspective

» I've been lucky to have this platform from which to opine about the state of the composites industry, a privilege I was offered while at the JEC show in 2013. I was even luckier, when, in January 2015, I was formally offered the position of chief commercialization officer for the newly announced Institute for Advanced Composites Manufacturing Innovation (IACMI, Knoxville, TN, US). Underpinned by funding from the US Department of Energy (DoE), the Institute represents the largest investment by the US government in advanced composites outside the aerospace and defense industries. In my opinion, it offers a fantastic chance to ensure the US composites industry remains on par with the rest of the world, takes the lead in certain areas and commercializes world-leading technology in industrial applications.

> What if we took a "big hat" approach to reach faster, more cost-effective solutions?

I also participated in the formulation of IACMI's strategy and its winning proposal to DoE, over the course of 2014. I've spent my entire career in industry, working for large and small companies in various fields of composites. Although I knew a fair number of individuals who do the work on university research teams and in the national laboratories through professional societies and conferences, I had only infrequent, modest interaction with their employers. And it was those universities and national labs that comprised the majority on the IACMI proposal team.

What has been most eye-opening for me is the incredible number of truly brilliant people and the quantity of accessible assets that exist in the IACMI ecosystem, of which I, an involved industry veteran, was not fully aware. The universities and national labs have accrued significant leading-edge experience in many aspects of composite materials and structures and have amassed analytical equipment (some of it very expensive and specialized) and manufacturing processes at various scales. And this will *expand* as IACMI launches its forthcoming scale-up facility in Detroit, where full-sized automotive structures will be fabricated, and at the modeling-and-simulation hub at Purdue University in Indiana, which will host much of the world's leading composites design and process simulation software. I believe accessing these capabilities is important to businesses of any size, but especially to small and medium enterprises (SMEs), for which making such investments in capital and talent are often cost-prohibitive and a significant barrier to developing innovative solutions.

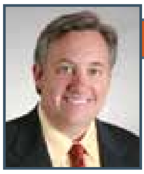
During my time with Quickstep Composites (Dayton OH, US), we conducted some high-speed crush testing at Oak Ridge National Laboratory (Oak Ridge, TN, US) and some mechanical testing at University of Dayton Research Institute (UDRI, Dayton, OH, US), but clearly overlooked some other opportunities due to our small size. An important part of IACMI's mission will be to help SMEs tap into this talent and equipment at a fraction of the full cost, partly due to matching support from DoE and state investors, and to do so flexibly and responsibly.

Such capability is not limited to IACMI. Excellent support is available to industry at universities, each with a strong composites heritage, on the US East and West Coasts. In fact, the same is true via institutes and universities *across the globe*. I've been fortunate to have met with the leadership of many of them in Canada, the UK, France, Germany, Australia and elsewhere. A number of IACMI member companies are multinationals that also invest in other institutes and sometimes have to decide which projects to place where.

That begs a big question: Do these institutes need to "go it alone"? Why can't they leverage their investments to *jointly* tackle some of the biggest challenges, such as embodied energy, confidence in predictive modeling, recycling and high-speed manufacture of complex shapes from continuous fiber materials? The problems we face here are not trivial impediments to expanding the market for advanced composites and, given the global nature of competition, our solutions would be adopted around the world. I believe there is a need to establish lines of communication, and even explore potential collaboration, between IACMI and the world's other composites institutes.

Yes, it's problematic: Most institutes that work on composites have some level of regional or national public funding justified on the premise that such investment in technology development creates needed jobs and industrial capital investment. The natural tendency, then, will be to resist open collaboration in hope of developing first-mover advantage, typically manifested in higher exports or reduced imports of goods. But international collaboration has the potential to reach solutions faster and in a more cost-effective manner, which benefits *everyone's* government investors and industrial partners simultaneously. It's a "big hat" mentality. It's also, no doubt, a challenge to execute, especially as we consider how to share the costs, effort and resulting intellectual property.

Can we make it work? We won't know unless we give it a go. CW



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Laminated composites: The original additive manufacturing process

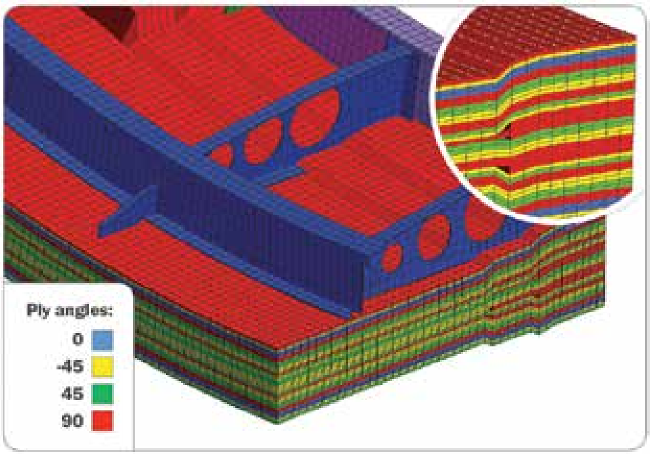
» There is a lot of enthusiasm around additive manufacturing (AM) these days. From high-end applications of AM, such as the GE fuel nozzle, to the home market and hobbyists fairs, AM has captured our imaginations and unleashed our creative instincts with the potential to make anything we can dream up. Many are new to the idea of AM and think of it as a very new technology. However, with a little research, you can find that stereolithography was introduced more than 20 years ago. Further, other common AM processes, such as selective laser sintering and fused deposition modeling (see Learn More), are well over a decade old.

If you look at the composites industry, one can claim that laminated composites are the *original* AM technology. The idea behind AM is that you build up a structure layer by layer to form the complete part, rather than the traditional subtractive process, where you take a block of something and remove material. I remember cutting plies in a university lab in the 1980s and laying them down to create laminated structures. Before that, I remember building a fiberglass kayak as a teenager in the 1970s by laying fiberglass mats over a mold and applying epoxy resin. Both of these activites can be considered additive processes.

One of the allures of AM is that it can be mostly automated — you give the machine a design file and it builds the part. In fact, one AM technology holds some promise for 3D printing in large format (see Learn More, p. 12). For composites, there has been a parallel effort to automate the composite lamination process. To that end, automated tape laying (ATL) and automated fiber placement (AFP) equipment has become so advanced that you can mostly automate the process of building up a customized laminated structure. These machines are used to build very large aerospace structures, and these processes are significantly speeding up the build time and ensuring more consistent quality and repeatability.

One of the cited advantages of AM is that it offers a lot of flexibility in part design. Many designers are taking their inspiration from nature, which has evolved in such a way that its structures are very specifically and efficiently enabled, in terms of shape and material composition, to carry the loads each will have to bear. The human body is a great example of efficient design.

Further, there are a lot of *composites* in nature — trees, plants, bones and more. These natural composites are not the quasi-isotropic laminates we commonly see employed for industrial composites. In nature, plant fibers, for example, are aligned with the primary load paths to provide stiffness precisely where it is needed. The lengths of the fibers and their orientations are continuously varied throughout the structure. We see a lot of effort these days to realize very organic-looking industrial designs, using AM to build integrated components that have internal structures that could not be manufactured, practically, any other way.



Mimicking natural composites

In animal and plant life, nature's composite building materials are not arranged, like our materials often are, in quasi-isotropic fashion. Here, composite ply optimization has been applied to mimic nature's practice of specifically and efficiently tailoring a structure for the loads it must bear. Material has been added where it will see higher stresses, with fibers oriented along the directions of major load paths.

Given the modern ATL and AFP equipment now in use, can we start to think of customized composite structures that are tailored and tuned, in a similar way, to specific applications? To do so, we will need design software that can help us determine where we need those fibers, what their orientations and lengths should be, as well as when to vary the fiber/matrix percentage and matrix properties. The good news is that much of the design optimization software, such as topology optimization, genetic algorithms, neural networks, etc., were inspired and developed to *mimic* natural biological processes. Because nature is very efficient in the design of composite structures, these algorithms can help us design more efficient industrial composite structures. Using these algorithms, we can start to design composite structures that are truly optimized for function, and with the new, automated composite manufacturing equipment, we can build up these structures in an efficient fashion.

As an example of this, the figure above shows an aerospace structure where composite ply optimization has been applied. The result shows added plies on the right side, where stresses are »

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higher, and an increase in the number of 90° plies in the thicker section (clearly shown in the "blow-up" image, in the top right-hand corner). Human bones are similar in construction — with added material where you see higher stresses, aligned fibers along the directions of the major load paths, and then tapered volume as the stress field decreases.

Because fabrication of laminated composites can claim to be the original additive manufacturing process, it also should be the most advanced in terms of application. Given the sophisticated automated equipment now in use for composite laminate layup and the design optimization software that is now available, we should truly be able to enhance our composite structural designs, and move them closer to the optimized designs that we see in the natural composites all around us. CW

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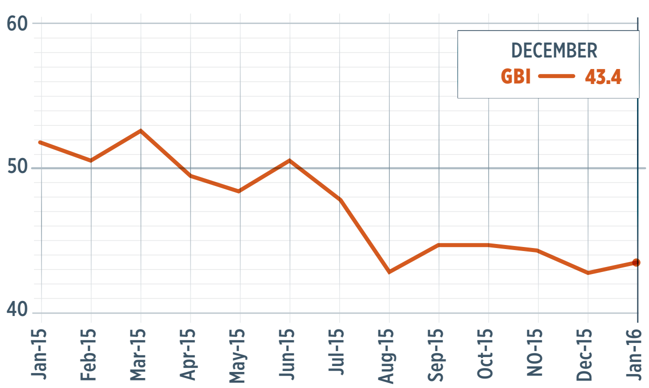
January 2016 — 43.4

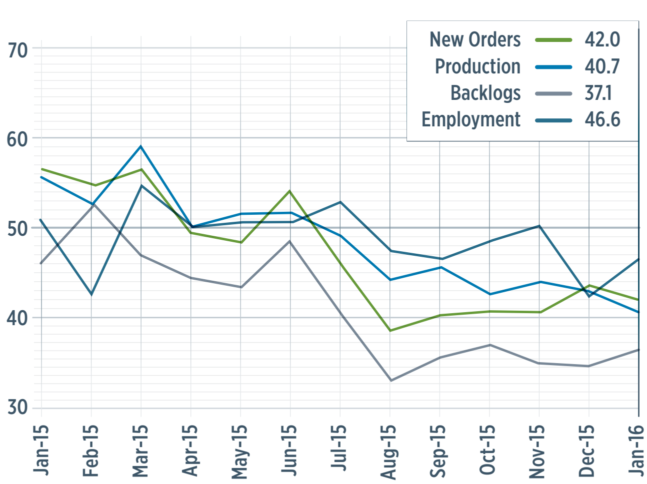
Mid-sized U.S. production facilities expand; capital spending plans reach second highest level since August 2015.

» With a reading of 43.4, the Gardner Business Index for the U.S. composites industry in January of this year showed contraction for the ninth time in 10 months. At that time, the rate of contraction had been virtually unchanged during the past six months, although the index did improve slightly from December 2015.

New orders contracted in January for the seventh month in a row. However, that subindex had contracted at a generally decelerating rate since August 2015. The production index had contracted seven months in a row, too. However, its rate of contraction had generally accelerated since July 2015. The backlog subindex continued to contract at a significant rate, but in January it had improved since hitting a low point in August. Further, the rate of contraction had slowed somewhat since then. But the trend in backlogs indicated falling capacity utilization at plants operated by composites fabricators. The employment subindex also contracted for the second consecutive month, exports continued to contract because of the strength of the U.S. dollar, and supplier deliveries lengthened in January after shortening in December 2015.

A GBI reading of >50.0 indicates expansion; values <50.0 indicate contraction.





Materials prices plunged in January, decreasing for the second month in a row. That subindex had dropped significantly since reaching a peak in July 2015. Prices received decreased for the fourth month in a row. In January, both of these subindices were decreasing at their fastest rates since the GBI's Composites survey began in December 2011. The future business expectations subindex in January dropped to its lowest level since November 2012.

After expanding significantly from September to November 2015, plants with more than 250 employees contracted in January for the second month in a row. The weakening conditions at large facilities had been a significant reason for the decline in the overall index. While the largest facilities experienced contraction, plants with 100-249 employees expanded for the third time in four months. Facilities with 50-99 employees continued to contract but posted their highest subindex figure since June 2015. Companies with 20-49 employees contracted at their fastest rate since the survey began, while fabricators with fewer than 20 employees saw conditions improve notably in January.

The four largest markets served by composites fabricators, based on the primary NAICS codes of *CW's* circulation list, are *job shops*, *automotive*, *custom processors*, and *aerospace*. At the end of January, job shops had contracted for the preceding seven months while custom processors had contracted five of the previous six months. The automotive industry had mostly expanded since December 2013, but had contracted for three months. The aerospace industry had expanded significantly in October and November but then contracted significantly for two months.

Future capital spending plans in January reached their second highest level since August 2015. But they were still noticeably below the historic average and had contracted 24.3% compared with one year earlier. CW

ABOUT THE AUTHOR

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IACMI and NAIAS meet and mirror composites industry potential in Detroit, Sierra Nevada gets second shot at ISS missions, vehicular bridge deck tech premieres.

IACMI starts to hit its stride

The Institute for Advanced Composites Manufacturing Innovation (IACMI, Knoxville, TN, US) held its second membership meeting in Detroit, MI, US, Jan. 13-14, to coincide with the North American International Auto Show (NAIAS). The meeting was the first since formation of the US$259 million public/private consortium designed to accelerate composite materials and process development in June 2015, and it was held to bring members (suppliers, OEMs, academia, government officials) up to speed on the consortium's activities. IACMI is organized around five focus areas: automotive, pressure vessels, wind, process engineering and design engineering. There are specific goals associated with each area. IACMI members are encouraged to develop collaborative partnerships to pursue projects affiliated with a goal or goals, and then solicit funding from IACMI. Projects can be developed *ad hoc*, or organized to meet a request for proposal (RFP), the first of which IACMI issued in fall 2015.

Detroit Mayor Mike Duggan touted Detroit's resurgent manufacturing economy. Source | IACMI

The headline news at the meeting was the announcement by Larry Drzal, IACMI's director, vehicle technology area (VTA), and Ray Boeman, associate director, VTA, of the establishment of an IACMI technical center in the Corktown neighborhood of Detroit, which will be used for R&D and pre-production operations for prepregging, resin transfer molding (RTM), compression molding, injection overmolding, finishing and material formulation. IACMI will have 2,880m^2 of high-bay space and more than 743m^2 of additional space shared with the Detroit-based Lightweight Innovations for Tomorrow (LIFT) consortium.

For proof of innovation progress, IACMI offered Dr. Felix Nguyen, principal research scientist at Toray Composites (America) Inc. (Tacoma, WA, US), who talked about a collaborative effort with Tacoma-based Globe Machine Manufacturing Co., Janicki Industries (Sedro-Woolley, WA) and RocTool (Charlotte, NC, US) to develop fast-cure prepreg materials for automated compression molding of automotive composite parts. Peter Fritz, engineering specialist at Eaton, discussed his company's IACMI proposal to develop a composite differential case for automotive driveline use that could show mass savings of 40-50%.

Doug Adams, technical fellow in nondestructive evaluation (NDE) at Vanderbilt University, talked broadly about IACMI's goals to improve composites fabrication process control and discussed the role that robust NDE might play. Specifically, he addressed the need for faster, large-area NDE technology that enables fabricators to assess process and product quality in real time, when it is easiest and least expensive to correct errors. He also discussed the value cure-monitoring technologies offer those who seek to optimize fabrication processes and avoid part over-cure.

Craig Blue, IACMI's CEO, kicks off the winter meeting in Detroit. Source | IACMI

Dale Brosius, IACMI chief commercialization officer, walked the membership through the consortium's goals for the five years covered by the program's initial funding window. At the top of this list is to ensure IACMI is sustainable *beyond* that window. That will require that many initial goals be met, including a 25% reduction in carbon fiber composite cost, a 50% reduction in carbon fiber composites embodied energy and 80% composites recyclability into useful products. In addition, IACMI is tasked with reducing lifecycle energy consumption, increasing domestic production capacity, job growth and establishing an advanced training program. The first commercialization of an IACMI technology must be achieved by month 24; 20 more must follow *and* 500 people must complete the IACMI training program, all within the five-year timeframe. Read Brosius' commentary on IACMI's gathering on p. 8.

IACMI is still accepting membership applications. Interested companies and organizations are encouraged to contact the consortium to explore options and costs. The next IACMI membership meeting will be in July at Purdue University in West Lafayette, IN.

For more information about IACMI membership, visit **iacmi.org/membership**

ENERGY

Wind energy scores record gains in 2015

The numbers from 2015 continue to roll in, adding to 2015's status as a stellar year for composites as an enabling technology in the energy market. Denmark reportedly set a world's record for energy generation from alternative resources in 2015, using wind turbines to generate 42% of the country's electricity. In 2014, the figure was 39% — also a world record, that according to Energinet/DK, a non-profit enterprise owned by the Danish Ministry of Energy, Utilities and Climate. Energinet/DK also reported that, at times, its wind farms produce a surplus of energy that can be sold to consumers in Norway, Sweden and Germany.

Meanwhile, the BBC reported that wind farms in Scotland, while not able to put the UK as a whole in front of Denmark in terms of total wind energy production, neverthless generated enough electric power to supply the equivalent of the electrical needs of 97% of Scottish households in 2015 and that its capacity had increased by 16% since 2014. (*continued on p. 18*)

(*continued from p. 17*)

Overall, the European Union installed a recordbreaking 12.8 GW of wind capacity last year, according to the European Wind Energy Assn. (Brussels, Begium). With that, wind bested hydropower, and is now the EU's third-largest source of electricity. Wind, in fact, has accounted for one-third of all new electric power-generating installations since 2000 in the EU, says the EWEA.

In the US, the American Wind Energy Assn. (Washington, DC, US) reported that wind accounted for 47% of all new power generation brought online in 2015. The US added a total of 14.468 GW to its installed capacity last year. Wind added more capacity in 2015 than any other energy source, and it was followed by natural gas at 35% and solar at 14% (figures were compiled by SNL Financial LLC, Charlottesville, VA, US | **https://www.snl.com/InteractiveX/Article.aspx?cdid=A-34950800-13103**).

AWEA also says the data showed that the state of Texas, once best known as a center of the US oil industry, led the pack. The Texas Reliability Entity region added more capacity from renewable sources than any other region last year, and wind accounted for almost 69% of that total. Wind energy recently supplied 40% of Texas' entire demand for 17 hours in a row, a new record. At its zenith, wind made up 45% of the state's energy generation mix. ERCOT, the main grid operator for most of Texas, announced that in 2015, overall, wind was responsible for 11.7% of Texas' electricity generation. That surpasses nuclear power, to make it the state's third largest source.

INFRASTRUCTURE

Damage-propagation-resistant FRP: From bridge deck to canal lock


Source | FiberCore Europe

"In the 1990s and early 2000s, infrastructure made using composites was the Holy Grail," says FiberCore Europe (FCE, Rotterdam, Netherlands) founder Simon de Jong. A prime target was replacement of steel and concrete vehicular bridge decks with decks of composite construction. But in his company's experience, the Grail remained out of reach, due to cracking, delamination and debonding. "The Achilles' heel for fiber-reinforced plastics (FRP)," he explains, "has been durability under long-term, heavy loading *after* serious impact damage."

FCE claims to have alleviated this issue via its patented InfraCore Inside technology, which has evolved beyond the conventional sandwich box beams between FRP faceskins used in vehicular decks to a design featuring multiple z-shaped, two-flanged web structures that are overlapped and then faced to form an extremely robust construction. "This is a much different approach vs. using pultruded or infused FRP elements and then joining them," de Jong points out. "We have demonstrated that even with damage simulating impact from the edge of a steel shipping container, InfraCore Inside bridge structures can go on to sustain over 30 million load cycles from a real freight truck with no propagation of damage and the same strength and stiffness properties compared to pre-damage evaluation." Testing completed at TU Delft (Delft, The Netherlands) and Chalmers University (Goteburg, Sweden) has shown InfraCore FRP bridge decks can perform in this manner for a single-axle load of 320 kN, two wheels per axle, with each wheel print measuring 0.35m by 0.6m.

A 142m bridge span over the A27 motorway near Utrecht (see photo, p. 22) features seven prefabricated InfraCore composite bridge deck segments joined and subsequently coupled to a steel support truss to (*continued to p. 22*)

(*continued from p. 20*)

achieve a EuroCode vehicle traffic load rating of 60 MT. The FRP deck weighs only 140 kg/m² compared to 220 kg/m² for a steel deck, resulting in an overall deck weight reduction of 72,000 kg.

The InfraCore deck sections were molded with accurate recesses for slotting connections, a water drainage gutter and integrated cable tray. Deck materials are dry, noncrimp E-glass fabrics and foam core. Notably, the latter acts as a mandrel and performs no structural function. The layups were infused with polyester resin per a design that orients fibers in multiple directions to provide a semi-plastic failure mode with redundant load paths that provided for residual load-bearing capacity.


Source | FiberCore Europe

Deck sections were transported to the bridge site by road, assembled with the steel truss supports and moved into place using self-propelled modular transporters. The underlying motorway was closed only for portions of two subsequent evenings, further reducing overall project cost. In the end, the InfraCore hybrid cost the same, upfront, as an all-steel solution, but offers longer service life, lower maintenance costs and fewer CO_2 emissions during production.

This same technology has now enabled the world's largest set of FRP canal lock gates (see photo, p. 20). They measure 3m tall, 6m wide and bridge an overall 13m difference in water height, installed in the Wilhelminakanaal (Tilburg, The Netherlands). For the client Rijkswaterstaat, part of the Dutch Ministry of Infrastructure and the Environment (Utrecht, The Netherlands), FCE's InfraCore Inside is no longer on trial but, instead, a proven technology: Contractor Heijmans (Rosmalen, Netherlands) installed eight FCE InfraCore FRP lock gates in 2015.

As a result of these successes, FCE has set its sights on reducing the budget for roughly 1 million bridges in the EU that need renovation. "We have engineered a renovation process with InfraCore that could save more than 10% of the estimated cost, or €7 billion," says de Jong. As part of an EU project that also involves the US Army Corps of Engineers, FCE will complete engineering, testing and validation of the financial savings that might be possible over the coming two years.

AUTOMOTIVE

What the Detroit Auto Show does and does not show


Source | CW / Photo | Jeff Sloan

If you walked this year's North American International Auto Show (NAIAS, Detroit, MI, US, Jan. 11-24), it was not difficult to get excited about the automotive industry. There was the inevitable glitz — bright lights, loud music, big crowds — but there also was substance. Attractive concept cars and the latest and greatest production vehicles, ranging from two-seater all-electrics to gargantuan pickups provided ample evidence of the automotive industry's energy and conveyed a distinct sense of optimism about where this market is headed.

It also was not difficult to detect the influence of composites. Automakers that use carbon fiber made sure that the tell-tale black (and in one case, blue) weave was in viewer sight lines on high-visibility parts. Indeed, carbon fiber could be found on rearview mirrors, interior trim parts, roofs and the exterior trim of concept cars. And then there was the carbon fiber you could not see (or not see so easily), including that used in the monocque passenger cell of the BMW *i8* and *i3* and the Alfa Romeo *4C Coupe* and *Cabriolet.*

Viewed from the overall perspective, however, the 2016 model year vehicles at the show represented automotive technology that is, for the most part, about two years old. That is, the design cycle of the automotive industry forces automotive OEMs to work ahead of itself, which means that much of the materials technology on the floor in Detroit was conceived in the 2013-2014 timeframe. So, for all of the talk of late about the incursion of composites into automotive structures, it will likely be a year or two before the world sees the production vehicles that will result from that incursion, featuring greater use of composites in structural applications.

Then again, it's likely that whatever the casual observer sees of composites in 2018 at the NAIAS will look a lot like it did in 2016. Visible carbon fiber will have its emphasis, and all of the other carbon fiber — likely a lot more of it — will be out of direct sight. In any case, composites of any kind, to have a seat at the table, must perform with adaptability, flexibility and speed. If, in fact, automakers are becoming increasingly "material agnostic," then all of the materials at their disposal must be adaptable to a variety of designs and applications. Motorists, after all, are buying vehicles to meet their transportation needs, *regardless* of material.

So, *CW* will check in with the NAIAS from time to time for a holistic view of how the automotive world is evolving, but stay focused on those structures that are a little harder to see.

CW MONTH IN REVIEW

Notes on newsworthy events recently covered on the *CW* website. For more information about an item, key its link into your browser. Up-to-the-minute news | www.compositesworld.com/news/list.

CFM: LEAP engine orders exceed 10,000
Aircraft engine maker CFM International booked 2,154 engines in 2015, produced 1,638 engines and has a backlog of 13,400 engines.
02/08/16 | short.compositesworld.com/LEAP-10000

Haydale opens composite pipe testing facility
The facility, in the UK, offers short- and long-term pressure testing of composite pipes up to 500 bar and at temperatures up to 80°C.
02/08/16 | short.compositesworld.com/HaydaleTst

Suzlon opens blade science center in Denmark
The center, in Vejle, Denmark, will focus on developing turbine blades and control systems to help maximize the levelized cost of energy in wind turbines.
02/08/16 | short.compositesworld.com/SuzlonCtr

James Webb Space Telescope primary mirror fully assembled
The mirror consists of 18 primary mirror segments, each 1.3m wide and mounted on a composite backplane structure. The telescope will be launched in 2018.
02/08/16 | short.compositesworld.com/WebbMirror

Marine Concepts/JRL Ventures acquired by Leisure Product Holdings
The Florida, US-based composites manufacturing and design/engineering specialists join Leisure Product Holdings' family of marine-based manufacturing firms.
02/08/16 | short.compositesworld.com/MC-JRLacqur

Siemens in talks to acquire Gamesa
A merger of the two companies, if completed, would create the world's largest wind turbine manufacturer.
02/01/16 | short.compositesworld.com/GamesaBid

Sandvik Coromant acquires Prometec GmbH
Germany-based Prometec specializes in advanced solutions for monitoring and control of machining processes, especially in automotive applications.
02/01/16 | short.compositesworld.com/SandProm

Huber acquires Martinswerk business from Albemarle
The Martinswerk portfolio is now part of the Huber Fire Retardant Additives business unit.
02/01/16 | short.compositesworld.com/HuberMart

Boeing's 737 MAX completes first flight
Boeing's 737 MAX 8, featuring composites-intensive LEAP-1B jet engines from CFM International, is expected to enter service in third quarter 2017.
02/01/16 | short.compositesworld.com/737MAX1st

FACC provides outboard flaps for the A320neo family
The Ried im Innkreis, Austria-based airframer credits increased efficiency to new production methods, including robotic systems and automated tape laying.
01/25/16 | short.compositesworld.com/FACC320neo

AEROSPACE

Hexcel core factory to augment growing Moroccan aerospace community

Hexcel (Stamford, CT, US) announced that it will build a 10,870m² manufacturing plant in Casablanca, Morocco. The new facility is part of Hexcel's ongoing effort to diversify its global aerospace supply chain to support customers' growing demand for engineered honeycomb core used in composite sandwich constructions for lightweight aircraft secondary structures, nacelles and helicopter blades.

In recent years, Hexcel has increased its capacity at existing plants to support current engineered-core business and plans further expansions to capture additional opportunities. The new Moroccan plant will be built at the MidParc Free Trade Zone (FTZ) Industrial Park, located near Morocco's Mohammed V airport and existing facilities operated by several Hexcel customers, including Safran (Aircelle, Gonfreville-l'Orcher, France), Airbus (STELIA Aerospace), Matis Aerospace (a joint venture between Boeing and Safran) and Bombardier (Montrèal, QC, Canada). Construction on the US$20 million project begins in the spring, and the plant is expected to be fully operational by mid-2017. By 2020, it is expected to employ more than 200 people.

Hexcel's chairman, CEO and president, Nick Stanage, says, "We believe engineered core has an excellent growth outlook and global upside potential. This new plant will position us to win new business to supply engineered core for engines and nacelles and other commercial aerostructure applications. We expect to partner more closely with our key customer base in Europe, Middle East, Africa and North America through this new Moroccan center of excellence."

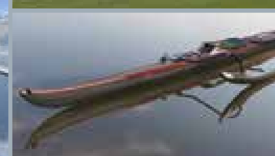
Bob Noble, VP, partnering for success, supplier management, Boeing Commercial Airplanes, says, "Through our joint venture, Matis, Boeing has been an anchor of the growing Moroccan aerospace ecosystem since 2000. We welcome Hexcel's new facility, which will serve to further expand regional capabilities, increasing the value Morocco offers aerospace companies around the world."

BIZ BRIEF

DolphiTech (Raufoss, Norway) and **Sonatest** (Milton Keynes, UK) have signed a global distribution agreement where Sonatest will market a specially branded version of DolphiTech's ultrasound inspection camera. The SonaCam, a mobile and ergonomic ultrasound camera system, is designed for NDT inspection of CFRP. A dry and wet transducer technology creates 2D and 3D images of suspected damage areas to verify the status of the material, and helps manufacturing and service personnel to perform effective QA and to develop the best repair strategy for a damage.








AEROSPACE

NASA selects Sierra Nevada for ISS cargo transport contract

In news seen as a big win for the company that was the sole loser during the competition for the coveted NASA contract to transport US astronauts to and from the International Space Station (ISS, see end note), Sierra

Source | Sierra Nevada Corp.

Nevada Corp. (Louisville, CO, US) was recently awarded a contract from NASA to launch cargo resupply missions to the ISS. Sierra Nevada will join Orbital ATK (Dulles, VA, US) and SpaceX (Hawthorne, CA, US) to continue building on the initial resupply partnerships.

These Commercial Resupply Services (CRS-2) contracts are designed to obtain cargo delivery services to the space station, carry out disposal of unneeded cargo, and return of research samples and other cargo from the station back to NASA facilities on the grund.

While the maximum potential value of all contracts is US$14 billion from 2016 through 2024, NASA will order missions as needed, and the total prices paid under the contract will depend on which mission types are specified.

Sierra Nevada has developed the winged, composites-intensive *Dream Chaser* spacecraft for low-G-force atmospheric re-entry and the ability to land horizontally on a runway. It's folding-wing design reportedly allows the *Dream Chaser* spacecraft to fit inside existing launch vehicle fairings, making it compatible with a diverse suite of rockets and assuring ready access to space orbit.

The contracts, which begin upon award, guarantee a minimum of six cargo resupply missions from each provider. The contracts also include funding for ISS integration, flight support equipment, special tasks and studies, and NASA requirement changes.

Selecting multiple providers assures access to ISS so crewmembers can continue to conduct the vital research of the National Lab. Awarding multiple contracts provides more options and reduces risk through a variety of launch options and mission types, providing (*continued on p. 32*)

(*continued from p. 30*)

the ISS program a robust portfolio of cargo services that will be necessary to maximize the utility of the station.

NASA has not yet ordered any missions, but each will require complex preparation and several years of lead time. Discussions and engineering assessments will begin soon, leading to integration activities later this year to ensure all space station requirements are met, with the first missions beginning in late 2019.

"These resupply flights will be conducted in parallel with our Commercial Crew Program providers' flights that enable addition of a seventh astronaut to the International Space Station. This will double the amount of crew time to conduct research," says Julie Robinson, chief scientist for the ISS Program. "These missions will be vital for delivering the experiments and investigations that will enable NASA and our partners to continue this important research."

Read more about Sierra Nevada's efforts to gain NASA mission contracts online | **short.compositesworld.com/SpaceTaxi** and **short.compositesworld.com/DC-Blog**

BIZ BRIEFS

Solvay SA (Brussels, Belgium) signed an exclusive distribution agreement between its recently formed Composite Materials Global Business Unit and **Bang & Bonsomer Group AB** (Helsingfors, Finland). It covers Lithuania, Estonia, Latvia and Finland for all Process Materials products. The Process Materials portfolio includes an extensive portfolio of vacuum bagging consumables, kitting solutions, tooling products, and composites materials for aerospace, automotive, wind energy, marine and other applications.

Hexcel (Stamford, CT, US) announced that it has acquired full ownership of **FORMAX UK Ltd.** (Leicester, UK). Hexcel had previously acquired a 50% interest in the privately owned company in December 2014. FORMAX, a manufacturer of composite reinforcements, specializes in lightweight carbon fiber multiaxials and highly engineered glass and aramid fiber fabrics. The move will enable Hexcel to further advance dry reinforcements technology for aerospace applications and provide scale for growing industrial markets.

Consolidation in the fiberglass segment

Owens Corning (Toledo, OH, US) announced in late January that it has signed an agreement to acquire the glass nonwovens and fabrics businesses of Ahlstrom (Helsinki, Finland), a fiber-based materials company. The acquisition cost is reportedly €73 million (US$79.5 million). The transaction, which is subject to customary regulatory approvals, is anticipated to close in the first half of this year.

The assets to be acquired include operations in Karhula and Mikkeli, Finland, and Tver, Russia. Collectively, the facilities employ ~260 people and showed reported 2014 sales of €77 million (US$85 million). The operations in Karhula and Tver produce glass nonwovens, primarily for flooring applications, and the facility in Mikkeli produces fabrics, primarily for composite wind turbine blades. Owens Corning says the addition of the Ahlstrom assets will strengthen its position in the nonwovens, high-modulus glass and specialty fabrics segments, particularly in the wind energy sector. In doing so, it will also provide a broader, multi-region supply base across Europe, North America and Russia, enabling it to serve customers in those locations more efficiently.

The transaction also reflects Owens Corning's ongoing commitment to grow its downstream composites businesses and is consistent with its investment in the construction of a new glass nonwovens facility in Gastonia, NC, US, which will begin production in early 2016.

"The planned acquisition of Ahlstrom's glass nonwovens and fabrics businesses is a winning combination for our customers, our markets and our employees," says Arnaud Genis, group president of Owens Corning's Composite Solutions Business. Marco Levi, Ahlstrom's president/CEO, adds, "We are happy to have found Owens Corning as the buyer, as it's vertically integrated and has ample resources to develop the glass fiber business further."

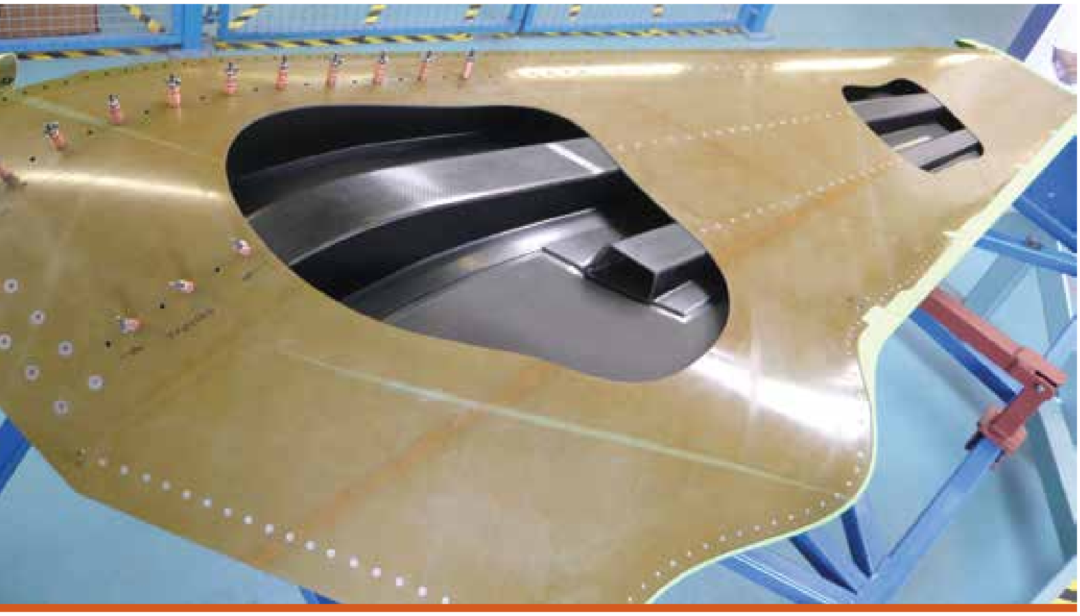


FIG. 1 Fewer steps, shorter cycle, comparable part

The Advanced Winglet Program aimed to replace the conventional metal ribs and CFRP spars clad in CFRP skins, with a one-piece, co-cured upper skin and waffle stiffener. Here, the new winglet has the lower skin cut away to show the stiffeners.

Source | GKN Aerospace

GKN leads STeM Program to successful conclusion

Technical achievements are credited to successful partner collaboration.

By Bob Griffiths / Contributing Writer

» In Europe and North America, many composites developments are undertaken by groups of companies working in collaboration. These efforts are encouraged by funding at either the level of the local state, or at higher levels, such as the European Union or, in the US, national government agencies. The obvious aim of these programs is to raise the Technology Readiness Level (TRL) of new manufacturing processes, but an equally important effect is to encourage competitors to collaborate locally, increasing the quality of work and forming a basis for possible business developments that stimulate economic health.

One such program, the Structures Technology Maturity (STeM) project, began in the UK in April 2012 and was completed in 2014. The partners were GE Aviation (Hamble, England), Bombardier Aerospace (Belfast, Northern Ireland), Spirit AeroSystems (Prestwick, Scotland) and the program leader, GKN Aerospace (Isle of Wight, England). Funding came from the UK government, via its Technology Strategy Board (TSB), now known as Innovate UK, and, therefore, was available to all companies with business locations in the UK, a fact that benefited the three of the four partners that are owned by North American corporations.

Axillium Research (Daventry, UK), which acted as the Project Management Support Office, both for the program and its partners, ran an initial workshop, which determined how teams were formed for each theme. As a result, the partners worked (or didn't) on various topics, depending on their interests. For example, Bombardier and GKN Aerospace worked on hollow structures, but *all* the partners were involved with modeling of springback phenomena.

The program manager was Craig Carr, from GKN Aerospace, and the TSB monitor was Ray Browne. The TSB described the program as Exemplar, an example that others should strive to follow in respect to what it achieved and how it was run. Carr believed the project received this rating not only for its technical achievements but also for the excellent collaboration between the partners.

The program looked at a number of different structures, among them a winglet and a main wingbox rib (see Fig. 1, above). The Advanced Winglet Program, carried out at the GKN Aerospace facility on the Isle of Wight, aimed to replace the traditional design of metal ribs and CFRP spars clad in CFRP skins, with a one-piece, co-cured upper skin and waffle stiffener (see Fig. 2, p. 35). To this,

FIG. 2 Upper skin/stiffener

The winglet's one-piece, co-cured upper skin and waffle stiffener, fully exposed. Source | GKN Aerospace

FIG. 3 Automated assembly

The winglet's lower skin is mechanically fastened during a highly automated assembly process. Source | GKN Aerospace

FIG. 4 Robotic manufacture

Identical Coriolis Composites (Queven, France) AFP robots installed at the National Composite Centre (Bristol, South Gloucestershire, UK) were able to build the Advanced Winglet's complex lower skin in 70% less time than that required for a conventional winglet's lower skin. Source | GKN Aerospace

the lower skin would be mechanically fastened by a highly automated assembly process (see Fig. 3, center left). Other than the tip and the leading edge, the structure was entirely composite.

The lower skin was manufactured using robots equipped with automated fiber placement (AFP) heads (see Fig. 4, bottom left) from Coriolis Composites (Queven, France). These were used to produce a complex, highly optimized layup only constrained by the need to fit the compact Coriolis head into the tight radius of the component. The manufacturing times were reduced by 70% compared to those of a conventional structure. For this initial program, the upper skin could not be optimized, because it was layed up manually, but in a follow-on program, both skins will be made with an AFP system to match a fully optimized design.

In-process inspection was used to monitor the quality of parts made during this project. It used an infrared camera to monitor the small temperature differences as the skin cools from the heat input of the AFP machine, as in a thermographic nondestructive testing (NDT) machine. The process called attention to any bridging or gaps between tapes. Two options for mounting the camera were tried. One had the camera mounted on the laying head and the other mounted it at a fixed point near the component. The latter, a more distant vantage point, made the camera less effective at finding small defects. When it was head-mounted, the camera yielded better image resolution of the defect, but had the disadvantage of increasing the size of the head (see Fig. 5, p. 36)., thus restricting the tightness of corners into which it could lay material. A "clash avoidance" simulation was developed to analyze the potential for head/tool collisions in such scenarios.

After the components were cured, ultrasonic C-scan NDT was used to detect voids. One innovative development demonstrated here was the use of a flexible transducer head. This had to be used because of the tight curvature of the component.

Another aspect of the program was to develop modeling techniques for the deformation of composites into complex shapes. Tim Dodwell from Bath University (Bath, UK) based his effort here on some work done in the early 1900s by two French brothers, Eugène and François Cosserat. This team, a mathematician and an engineer, applied modeling techniques to tectonic plates in the Earth's crust. Today, the same methods have been applied to composite laminates to capture the formation of defects in large parts and wrinkling in the radii of 2D corners. This technique's development has enabled computational tasks to be undertaken for a fraction of the cost of conventional techniques.

Although the use of composites has provided avenues for improvements in component design and manufacture, particularly reductions in parts count, because they enable the combination of multiple parts via one-shot manufacture, there remains a need to address the high costs of assembly. These include the ongoing cost of labor and the non-recurring cost of the fixtures to hold composite and metal parts that must be joined in the correct positions relative to one another.

Fixtures have been developed that replace very large and heavy steel structures with much lighter tooling. These fixtures feature »

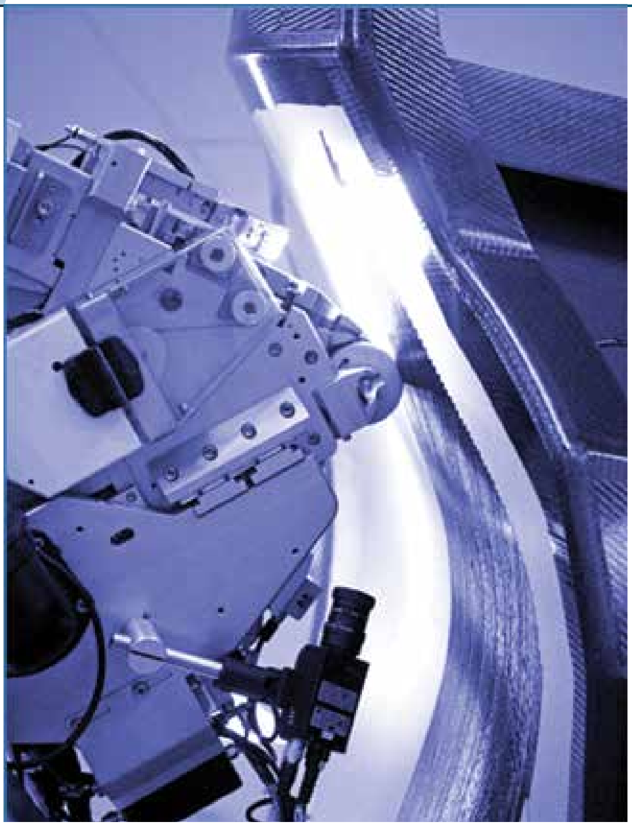


FIG. 5 Head-mounted infrared camera

An infrared camera was used to monitor small temperature differences as the winglet skin was placed by the AFP head. When it was mounted on the AFP head, it was most effective, but tended to restrict the tightness of radii into which the head could lay material. Source | GKN Aerospace

FIG. 6 Metrology assists critical positioning

Composites fixtures that replace heavier metal fixtures also feature *reconfigurable datum* — that is, they possess the capability to automatically adjust to variations in part thickness or shape. Source | GKN Aerospace

reconfigurable datum — that is, the fixture, by design, is able to cope with variations in the component parts, such as thickness or shape distortion. Metrology is used to assist critical positioning (see Fig. 6, bottom left). Notably, the cost of such tooling is less than half that of conventional fixtures. One recent comparison quoted was £200,000 (US$308,490) for conventional manually adjusted fixtures compared with only £50,000 (US$77,122.50) for new, lightweight tooling fixtures that, at the point they contact the part, can *automatically* adjust to part variations.

Robotic assembly was used with support from the AMRC (Rotherham, UK), based on earlier work done by Bombardier (Belfast, UK) with robotic drilling. It is anticipated that exploitation of the automation and advanced assembly methods may be used on future programs for civil and business jet major structures from parts made in the UK at GKN's composites facilities on the Isle of Wight and at the Filton Manufacturing Centre.

LEARN MORE

Read this article online | short.compositesworld.com/GKN-STeM

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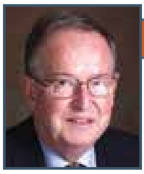
The benefits that the program demonstrated included:

- Overall cost savings of 17%, with weight neutrality. In the next phase, AFP will be used for the waffle and upper skin. This will save more weight, due to optimization of the layup that can be achieved by the use of AFP.
- The demonstration of achievable deposition rates 2x-4x faster than manual deposition, depending on the structure, compared with manual layup rates, will be used to develop the business case for future work.
- Projected investment savings of 50% by the application of automated drilling and filling.
- In-process inspection was successfully applied to an AFP head, and it was able to detect sub-surface defects.
- Advances in modeling deformations in composite plies in a number of common prepreg materials, such as Hexcel 8552, M21E and M91, using Cosserat modeling techniques.

Finally, this report on the project would be incomplete without noting the remarkable way the STeM partners, who are competitors in the aerostructures business, were able to work together, and that this not only worked to their mutual benefit but also was rewarded by funding to the same team for *another* project, VIEWS (Validation and Integration of manufacturing Enablers for future Wing Structures), started in April 2015. CW



ABOUT THE AUTHOR

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Oil & gas: Will the composite riser rise again?

A new effort to develop an undersea pipe resets the long-term development course, again, toward an all-composite design for deepwater-capable oil and gas risers.

By **Michael LeGault** / Contributing Writer

» The salt in seawater makes its oceans Earth's largest naturally occurring corrosive environment. Add man-made multipliers, such as high-temperatures and pressures and the host of aggressive chemicals, solvents and other fluids required to operate an offshore oil rig, and you have conditions that, over time, can be hostile to almost any material, but especially to metals.

No surprise, then, that inherently corrosion-resistant composite materials have increasingly been used to mold previously metal parts deployed in a host of offshore drilling platform applications. These include non-load-bearing topside platform components, such as fire-water mains, high- and low-pressure tubing, processing vessels and tanks, fire-blast panels, gratings and handrails, as well as newer subsea structures, such as carbon rod umbilicals and components for protecting wellheads, manifolds and other equipment related to subsea processing (see Learn More, p. 41).

Composites also are making tentative inroads into higher volume, more demanding offshore oil and gas applications, such as the pipes and pipe systems with which producers explore for oil, find it and eventually bring it up from the wellhead to the surface. Although many are still in development — a process that includes a lengthy and rigorous qualification phase — the impetus behind this R&D is seen by most everyone in the industry as significant. The question is not *if* but *when* offshore oil operators will be compelled to make greater use of lightweight composites in structural undersea pipelines.

This question is all the more critical as exploration companies develop subsea oil fields at greater distances from shore and at unprecedented water depths. In 2003 in the Gulf of Mexico, for example, only 35% of production was from wells at depths of >300m. By 2015 that figure was 95%. More to the point, more than 20% of Gulf wells are now at depths greater than *2,000m*. At these depths, conventional steel pipe systems pose serious logistical problems and tally huge costs. For example, *Thunder Horse*, the largest moored, semi-submersible oil platform in the world, is operated by British Petroleum (BP, London, UK) in partnership with ExxonMobil (Irving, TX, US) over a well in 1,920m of water, 150 miles off the coast of the US state of Louisiana. It began production in 2008, using a steel catenary riser (SCR) system, but the significant hang-off load created by the steel riser required the producers to spend US$5 billion to build a platform large enough to create displacement sufficient to counter-balance that load, together with costly buoyancy and tensioning systems.

"*Thunder Horse* was a wake-up call for the industry," says Bill Head, ultra-deepwater project manager at the Research Partnership to Secure Energy for America (RPSEA, Sugar Land, TX, US), a non-profit corporation under contract to the US Department of

■ **Offsetting pipe weight under massive offshore oil platforms**

Shown here on its way by barge to its moorings in the Gulf of Mexico in 1,980m of water, BritishPetroleum's (BP) *Thunder Horse* platform is now connected to a wellhead on the ocean floor via a steel catenary riser that created significant "hang-off" weight, which must be compensated for by costly displacement, buoyancy and tensioning systems. Oil production companies are actively seeking to qualify lightweight composite replacements for such heavy steel and flexible, unbonded risers. Source | BP

Energy (Washington, DC, US) to develop and enable technologies for secure, safe development of new US hydrocarbon resources. "People in the industry realized if they could make and deploy a lighter riser, they could potentially shave billions of dollars from the platform costs for these deepwater projects."

Indeed, for at least 20 years, composites have played an increasing role in the design of multi-layer, unbonded flexible pipe employed as dynamic risers, typically as glass- or carbon-reinforced internal "pressure sheaths" that replace tensile armor layers. For example, in 2000, Wellstream-Halliburton Subsea Systems (now Halliburton Energy Services, Denver, CO, US) qualified and built a 232-mm diameter flexible riser system that replaced steel armor with carbon-fiber thermoplastic composite, designed for service to water depths of 1,500m. The riser provided a weight savings of about 30% compared to conventional steel-lined risers.

Head reports that RPSEA is working with GE Oil & Gas (Houston, TX, US) to prototype and qualify an ultra-deepwater, flexible, unbonded riser with a steel core; as well as with Houston-based DeepFlex Inc. to do the same for a flexible, bonded steel-lined riser. (In both cases, the steel liner will be overwrapped with an unspecified laminate comprising carbon fiber and, perhaps, other reinforcements.) This construction promises a weight savings of 40-50% compared to conventional steel risers and, when qualified, will be targeted at new ultra-deep water applications. RPSEA also has partnered with Hexagon Lincoln Inc. (Lincoln, NB, US) to qualify a carbon fiber-reinforced steel dry tree drilling riser, suitable for ultra-deepwater and high-pressure applications. However, this, as yet, has not been deployed in a commercial operation. Aker Kvaerner Subsea (AKS, Lysaker, Norway) placed the first and, to date, only high-pressure composite drilling riser into service in the early 2000s, beneath Statoil's Heidrun platform in the North Sea, but even there, it was the second joint under the platform, far from the external pressures of deepwater operation (see Learn More).

Designing a deeper, lighter alternative

A new, recently announced joint development agreement by a group of companies might eventually result in one of the first, commercial, long-term, deepwater, fully composite structural riser applications. A qualification program, funded in part by the UK's National Composite Centre (Gloucestershire, UK), will run about 30 months and aims to qualify Magma Global Ltd.'s (Portsmouth, U.K.) fully-bonded, flexible, polyetheretherketone (PEEK)-infused carbon/S2-glass pipe, m-pipe, for a jumper application with an unprecedented service life requirement of 25 years.

Once the pipe is qualified, and if all goes according to plan, Magma's production partner in the project, BP, plans to install the jumper — within two to three years — at a West African field under development. The jumper pipe will be approximately 100m long, with a wall thickness of 20 to 25 mm, and will be used to connect two pieces of production infrastructure at a depth of 1,500-1,800m. The project's other partner, subsea engineering, construction and services company Subsea 7 SA (London, UK), will handle installation logistics. Although a jumper, obviously, is not a production riser, jumpers and risers are loaded, fatigue-sensitive structures subject to the same internal fluids, with test/certification parameters that are almost identical. Magma views success in this jumper qualification project as a key stepping stone to fully commercial, deepwater, *all-composite* risers.

Into position for all-composite commercial risers

Magma Global's (Portsmouth, UK) fully-bonded, flexible, polyetheretherketone (PEEK)-infused carbon/S2 glass "jumper" pipe is considered an intermediate step toward a commercial all-composite deepsea riser pipe. The pipe's alternating carbon/PEEK and S2-glass/PEEK layers and inner PEEK liner are clearly visible. On the sea floor, this design makes the jumper strong enough to withstand external pressure of 3,000 psi and internal pressure of 5,000 to 15,000 psi, but flexible enough to accommodate relative movement between connection hubs due to thermal expansion, and phenomena such as fluid slugging. Source | Magma

Adaptable for all undersea uses

Magma's m-pipe is a 100% bonded composite pipe comprising approximately 25% carbon fiber, 25% S2-glass and 50% PEEK. It's about one-tenth the weight of traditional steel and unbonded flexible pipe, and its thermoplastic matrix lends it the flexibility to resist damage from undersea flow. Source | Magma

M-pipe is a 100% composite pipe, comprising (approximately) 25% carbon fiber, 25% S2-glass and 50% PEEK, a construction that yields a pipe about *one-tenth* the weight of steel and traditional unbonded flexibles.

Unbonded pipe, as the name implies, comprises independent, unbonded layers, which by design may "slip" with respect to one another, providing inherent flexibility. By contrast, Magma's bonded m-pipe is manufactured by an automated tape laying (ATL) process, which fuses the alternating layers of glass and »

Physical Property	E-glass	S2-glass	T700 Carbon
Density (g/cm)	2.58	2.46	1.8
Tensile Strength (MPa)	3445	4890	4900
Tensile Modulus (GPa)	72.3	86.9	230
Elongation at Break (%)	4.8	5.7	2.1

Comparison of tested fiber physical properties

Three sets of fibers were evaluated for possible use as a reinforcement: Toray's T700 carbon, an S2-glass fiber and E-glass fiber.

carbon in a PEEK matrix — a design which requires that flexibility be achieved through material selection and layup architecture.

There were an assortment of daunting challenges, then, in designing, building and qualifying pipe for this application. For one, subsea pipe architectural complexities increase at greater sea depths. A typical subsea development can require many jumpers, which connect pipe "trees" to manifolds, and manifolds to pipeline end terminations (PLETs). Located on the seabed, jumper pipe must be designed to withstand high external and high internal pressures, but must be flexible enough to accommodate relative movement between connection hubs due to thermal expansion, pressure end-cap extension and riser loads. The jumper also will be subject to inertial and weight fluctuations due to internal *fluid slugging*, that is, variation in gas/oil flow rates. Finally, the jumper section must withstand vortex-induced vibration from ocean current flow across and around the pipe diameter.

"Designing a jumper for these applications boils down to finding a solution for a fatigue-sensitive problem," says Stephen Halton, Magma's technical director. "It is precisely the extremely high fatigue capacity of the PEEK and carbon-/S2-glass-reinforced laminate that makes it a strong solution." Additionally, Halton notes, the combination of a 25-year service life expectancy and deepwater installation required the design of a product with a set of performance requirements that would not only meet but *exceed* industry standards set for both carbon steel and unbonded flexible pipe. These included exceptional resistance to a variety of chemicals and fluids, high hydrolysis resistance, high operational temperature resistance and retention of modulus and strength with exposure to all these conditions.

To ascertain the most appropriate materials and fiber architecture for ultra-deepwater applications, Magma undertook a detailed materials characterization analysis, using available test data, much of it generated by and for the oil and gas industry. The spectrum of thermoplastics for the pipe precursor (inner wall) and the laminate matrix was pared down to four resins — high-density polyethylene (HDPE), polyamide-11, polyvinylidene fluoride (PVDF) and PEEK — which have been frequently used in the pressure sheaths of unbonded flexible pipe, as well as in connectors and other components.

A determining factor in PEEK's selection was its performance upon exposure to highly corrosive sour crude (oil containing 0.5% or more sulfur), a significant parameter because an increasing number of wells worldwide produce sour crude. PEEK has been evaluated in the standard NORSOK sour environment of 2% hydrogen disulfide (H_2S) in gaseous phase at 220°C, as well as 20% H_2S in gas phase at 220°C and 100% H_2S at 175°C and others. In all cases, PEEK showed no measurable loss of tensile strength after exposure up to 1,000 hours. PEEK also displays insignificant loss of mechanical properties when exposed to methanol (a common component of intervention fluids used in wells) at 175°C and 200°C, while other thermoplastics degrade rapidly under these conditions. Lastly, PEEK test data demonstrate its superior thermal performance with no loss of mass at temperatures up to 575°C, and excellent fatigue resistance as measured by tensile fatigue of the neat polymer with an endurance limit of 80 MPa — well above the stresses the pipe's precursor will see in operation.

Three sets of fibers were evaluated: Toray Industries' (Tokyo, Japan) T700 carbon, S2-glass and E-glass. The "Comparison of tested fiber physical properties" (top left) shows a comparison of each fiber's material and mechanical properties. S2-glass provides some improvement in stiffness and a significant boost in strength compared to E-glass; the T700 carbon fiber has a comparable strength to S2-glass but with about 2.5 times greater stiffness.

Fiber selection is a function of the loads the pipe will bear in a given application, Halton notes. Under high pressure, where flexibility is less important than high strength and stiffness, carbon fiber alone is suitable. Auxiliary lines, such as choke and kill lines for drilling risers, are examples of pipes that are often fabricated from carbon fiber. When pipe flexibility is more important than overall strength, e.g., in spooled intervention lines which have become a standard part of light-well intervention packages, a fiber with a lower modulus and higher elongation-at-break is preferable.

For the jumper, high strength *and* flexibility were required, to withstand external pressures up to 3,000 psi and internal pressures as high as 15,000 psi, yet permit bending, spooling and

Spoolable pipe for downhole applications

Magma's m-pipe is already qualified for use in shorter term downhole applications, such as this high-pressure water-injection line used at Enquest's Thistle platform in the North Sea, in place since 2012. Source | Magma ease of handling. Although S2-glass adds slightly to overall pipe weight (compared to carbon only), its higher strain-to-failure ratio compared to carbon reduces the bending stiffness, Halton reports.

Although he declined to specify the precise tape layup sequence, Halton reports that the company has qualified a "standard stack" laminate for m-pipe, which it intends to keep for the jumper qualification project. The laminate is built up layer by layer by the ATL process. The carbon fibers are aligned in the hoop direction for pressure containment, and the S2-glass fibers are aligned axially at 45° to enhance flexibility.

Qualification testing will proceed from laminate level to sub-scale pipe testing and then move to full-scale tests. When full commercial production commences, sections of pipe can be made in lengths as long as 4,000m, although typically, shorter lengths of about 1,000m likely will be fabricated and jointed. Although m-pipe's materials push it to a higher unit-to-unit price point than steel or unbonded flexible pipe, Halton says the sole consideration in the development of m-pipe was performance.

Again, Halton emphasizes, the company views the long-term *end-point* of the m-pipe qualification effort to be deepwater production risers. "We always intended to sell this as a solution to hang-off weight issues related to ultra-deepwater oil development and production." The layups of both pipes would be the same or very similar, he points out, noting that added axial fibers could resist the likely top-side tension needed at some platform locations. Volume production could moderate costs and consistency/repeatability would be ensured by manufacturing via ATL. With risers on the drawing board, the potential growth of composites in offshore oil could be as high as the ocean is deep. CW

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Automation: Robots taking off in commercial aircraft

Will this affordable and versatile class of multiaxis manufacturing hardware and software drivers enable airframers to reduce costs and speed deliveries?

By Donna Dawson / Senior Writer Emeritus

» The US Patent and Trademark Office (USPTO) reports patents granted in automation and control technology increased from 2,000 in 2004 to about 5,000 in 2013 — and that trend is expected to continue and could even escalate in years to come. A study by the Oxford Martin School, University of Oxford (Oxford, UK) in September 2013, found that about 47% of total US employment is at risk from computerization (defined as automation by means of computer-controlled equipment) of routine manufacturing tasks, but goes on to say that advanced robotic technology is capable of more. The study states: "The continued technological development of robotic hardware is having notable impact upon employment: Over the past decades, industrial robots have taken on the routine tasks of most operatives in manufacturing. Now, however, more advanced robots are gaining enhanced sensors and manipulators, allowing them to perform non-routine manual tasks."

FIG. 1 Robotic AFP

This 6.4m robot arm (KUKA Robotics Corp., Shelby Township, MI, US) incorporated into an Electroimpact (Mukilteo, WA, US) automated fiber placement system built for NASA is designed to lay up the largest one-piece launch vehicle components yet made. It is installed at the Composites Technology Center in NASA's National Center for Advanced Manufacturing at Marshall Space Flight Center in Huntsville, AL, US. Source | NASA/MSFC / Photo | Fred Deaton

FIG. 2 FAUB system

KUKA Robotics Corp.'s robotic equipment is a key component of The Boeing's Co.'s (Chicago, IL, US) FAUB construction of standard metal fuselage sections for the B777 commercial jet. Source | Boeing

In the US, robot orders for *automotive* manufacturing exceed orders for all other industries. In comparison, robot orders for *aerospace* manufacturing are currently not even on the charts. *CW* is hearing, however, that this is a growth market, and that Boeing, Bell, Bombardier and other aircraft OEM manufacturers — even in China, despite its historically low labor costs — are increasingly turning to robotic assistance, provided by a variety of robot manufacturers and related suppliers. Notable names in the composites world include ABB Robotics North America (Auburn Hills, MI, US), Fanuc Robotics (Rochester Hills, MI), KUKA Robotics Corp. (Shelby Township, MI), OC Robotics (Filton, Bristol, UK), Rethink Robotics (Boston, MA, US) and Hypertherm Robotic Software (Hanover, NH, US).

Robot manufacturers interviewed for this article see aerospace as an emerging growth market for robots. Robotic software producer Hypertherm believes "robots are poised to transform the aerospace industry the way they revolutionized automotive assembly" in the late 20th Century.

Aerospace manufacture, however, operates on a different paradigm: By comparison to those for automobiles, aircraft manufacturing tolerances are tighter, parts are larger and heavier, production volumes are significantly lower and the expected product lifecycle is longer by decades. That said, indications are that it might be possible for robots to provide the impetus needed for airframe manufacturers to soar past the "inflection point" and ramp up to the higher manufacturing volumes that will reduce the backlogs that are expected to increase in coming years.

Today, the highest-volume task for robots in aerospace is drilling holes for the tens of thousands of fasteners over the fuselage and wings of an airframe. "Rattling rivet guns are hard on the body, and a worker has to get into very oddly contorted positions to do some of that work, so that's the application that we see most often with the airframe manufacturer," says Dave Masinick, aerospace account manager for KUKA Robotics.

Robots are at work in numerous other aircraft operations as well, and although not all are composites applications, some robot manufacturers see composites as their next big growth area in aircraft manufacture. »

FIG. 3 ACSIS in-process inspection

The Automated Composite Structure Inspection System (ACSIS) for *in-process* inspection of automated fiber placement, under development by the National Center for Defense Manufacturing and Machining (NCDMM, Blairsville, PA, US), performs inspections in real time, as the part is manufactured. Source | Ingersoll

FIG. 4 RAMP adds z-axis fiber to 3D printing

The Robot-based Additive Manufacturing Platform (RAMP), developed by Arevo Labs (Santa Clara, CA, US), adds, for the first time, *z-axis* continuous fiber reinforcement to 3D printing capability. Shown here printing an automotive engine spare part, the system has recently been installed by a major aerospace company.

Source | Arevo

From gantry to robotic arm

In the composite arena, as in others, CNC machine tools that cost millions of dollars are being replaced by robots that cost thousands of dollars. One major composites function robots are performing is the automated fiber placement (AFP) and automated tape laying (ATL) of primary structures — notably wings, fuselage, fairings and rocket fuel tanks.

Commercially available multiaxial robotic arms from KUKA Robotics Corp., for example, are mounted on automated machine tool systems, which ride on linear tracks alongside the part tooling. Notably, newer robotic systems can easily be changed from AFP to ATL capability because the fiber or tape spools are mounted directly on the AFP or ATL head, which in turn is mounted on the end of the robotic arm (see "Learn More," p. 46). This comparatively simple system replaces the much more complex overhead gantry-and-bridge structure typically associated with conventional AFP and ATL systems: The gantry, which rides on two tracks in the x-axis, and the bridge, which provides motion in the y-axis, support the fiber or tape layup materials and the layup head that applies the material to the tooling. The head, attached to the bridge, draws fiber or tape from spools located in a separate creel, through a complex system that feeds fiber/tape to the head.

Masinick explains that robot-based systems are available more quickly than custom-built gantry systems, and they don't have to be re-engineered every time someone wants to build an AFP or ATL system for a new composite wing design or other part. The equipment system carrying the robot can be designed for the designated range of motion, and the length of the linear track can be varied for the length of the part. KUKA's KR-500 (500-kg payload capacity) or KR-1000 (1000-kg capacity) are typically used to carry an AFP head. KUKA partners with premier machine-tool manufacturers of systems for Boeing, Bombardier and others.

KUKA Systems Aerospace Group (Clinton Township, MI, US) developed a robotic system using KUKA robots for Boeing's Everett, WA, US-based Fuselage Automated Upright Build (FAUB) factory. The FAUB approach was introduced by Boeing for building standard metal fuselage sections for the 777. In late 2014, Electroimpact Inc. (Mukilteo, WA, US) won the award to provide Boeing robot-based AFP equipment, using KUKA robots, to produce carbon fiber composite wings for the 777X. (Electroimpact and Boeing, in fact, pioneered the one-machine, multi-head concept back in 2003-2004, and, in 2006, Electroimpact delivered an AFP machine complete with two easily interchangeable heads to Spirit AeroSystems, Wichita, KS, US, for layup of the Boeing 787's fuselage Section 41. See Learn More.)

Enabling NDI automation

Another important emerging application for robots is in aid of nondestructive inspection (NDI) of composite parts. As automated methods such as AFP and ATL reduced build time for wing, fuselage and other large aircraft structures, the mostly *manual* process of inspecting every part (a requirement for certified commercial aircraft) quickly became a production bottleneck. The result? Despite faster part *production*, lengthy backlogs and delays in customer deliveries persisted. Robotic scanning solutions have automated NDI, increasing its efficiency *and* freeing technicians to focus on the more important task of image evaluation rather than image acquisition.

KUKA Robotics and other robot manufacturers partner with companies that produce not only ultrasonic-, but X-ray- and laser-based inspection systems.

KUKA robots, in particular, can be found on ultrasonic NDI composite inspection systems by Genesis Systems Group (Davenport, IA, US) and on General Electric Measurement & Control's (Billerica, MA, US) patented Hydrastar single- and dual-robot ultrasonic inspection systems for composite parts such as spoilers, flaps and ailerons. Hydrastar replaces traditional gantry systems with two standard 6-axis robots mounted on linear tracks.

Thus far, however, NDI systems, manual or robotic, have enabled inspections *after* the part is cured — an additional step. A new robotic system is aimed at eliminating that step by enabling automated inspection *as the part is manufactured*. The Automated Composite Structure Inspection System (ACSIS) for *in-process* inspection of AFP is under development by the National Center for Defense Manufacturing and Machining (NCDMM, Blairsville, PA, US) in partnership with Ingersoll Machine Tools Inc. (Rockford, IL, US) and Orbital ATK (Dulles, VA, US). In October 2015, the partners announced the successful completion of Phase I of a three-year effort to place a system at the Air Force Research Laboratory (AFRL) at Wright-Patterson Air Force Base (Dayton, OH, US).

Manual inspection during such layups, of course, is not only time-consuming but challenging because defects are difficult to find visually. Even with proper equipment, manual NDI would be impractical. But because the ACSIS inspections occur in *real time*, at speed, *as* the composite structure is being fabricated, defects and anomalies, such as twisted fibers, voids and other flaws, can be found and repaired *before* cure.

For the ACSIS, Ingersoll incorporates a standard KUKA KR-16 robotic arm (16-kg capacity) into its AFP machinery design to carry the inspection scanning head. The robot/scanning head is programmed to follow the same path traced by the AFP layup head after it places each layer of carbon prepreg on the airframe tooling. The robotic NDI system reportedly will work with either gantry-based, horizontal or robotic AFP systems.

Although previous efforts to develop in-process inspection have not fully reached fruition, Phase I testing for the ACSIS reportedly achieved a defect detection rate of *up to 99.7%* during inspection of a part as it was laid up by AFP over a tool surface geometry that ranged from flat to complex (see Learn More). If this technology continues to display its early high percentage of success, then it will be a tremendous advantage to the Air Force and to airframe OEMs.

3D printing … in 3D

AFP/ATL and NDI are not the only aerospace-related technologies to benefit from robotic assistance. Additive manufacturing, also known as 3D printing, is a recent and *tool-free* addition to the aerospace manufacturing toolbox, and it's beginning to realize robotic advantages in aircraft applications. Additive manufacturing builds parts in thin two-dimensional layers, based on data drawn directly from CAD files. Although 3D printing processes bypass the toolmaking step, the composite parts that result are typically reinforced with milled or very short fibers. In the rare cases where the reinforcement is continuous fiber, the fiber orientation has been limited to the x/y dimensions inherent to the 3D printer's layering process.

Arevo Labs (Santa Clara, CA, US), however, has introduced an innovative process for exploiting multiaxis robots to "print" stronger parts with fibers oriented in *three* dimensions (x, y and z) for aircraft parts such as brackets, support structures, UAV bodies and wings.

Hemant Bheda, Arevo's co-founder and CEO, explains, "Our Robot-based Additive Manufacturing Platform (RAMP) produces complex parts in three-dimensional construction by utilizing the 6-axis capability of the robot." Specifically, a 6-axis robot, model IRB 120 from ABB Robotics, enables the addition of z-directional continuous fibers, which reportedly augment the strength of the part to as much as five times that of injection molded parts, using continuous carbon fiber-reinforced thermoplastics. The process reportedly also would work with glass fiber and, possibly, other thermoplastic resins but, as is the case with all current 3D printing processes, not with thermoset resins, Bheda notes. "We are currently focusing on high-performance polyetheretherketone (PEEK) and polyaryletherketone (PAEK) resins," he says, adding that the RAMP system has recently been installed by a major (unidentified) aerospace company.

Bheda notes that 3D printing offers the advantage of simplifying supply chain logistics by obviating the need for molds in the manufacture of many parts. This eliminates the need for making new molds as well as the necessity of storing active molds. »

SIDE STORY

Automation: Robotics in factory logistics

Robotic support

This 10-wheeled, 50-ton-capacity omniMove AGV, designed for carrying gas turbines for jet engines in and out of testing equipment, is similar to AGVs that can deliver parts to AFP or ATL systems or, as has become the practice more recently, delivering more compact robotic AFP/ATL systems to ever-larger parts. Source | KUKA

KUKA Robotics Corp. (Shelby Township, MI), has developed an automated guided vehicle (AGV) technology for logistics advances in aerospace. Its omniMove omni-directional transport device, says Dave Masinick, aerospace account manager for KUKA Robotics, "has a unique motion that allows moving very large, heavy pieces in very small confines."

The omniMove AGV is used, for example, to move fuselages and wings into position for final assembly tasks. The robotic AGV also replaces technicians in the even more difficult human task of transporting wingskin tooling that can weigh 11,340- to 13,600 kg to an automated fiber placement (AFP) system for layup, or to an autoclave after layup, or to a cleaning and storage area between process cycles.

The AGV's most recent and popular application, however, is transporting the robotic processing systems themselves. "Typically a part is moved to the robot, the robot does its work, the part is moved out and another part moved in," Masinick says. "But because these wings and fuselages are so large, it's easier to move the robot to the part tooling, than it is to move the part to a stationary robot. So omniMove is called in to work."

Robotic people-saver

KUKA Robotics Corp.'s (Shelby Township, MI, US) 56-wheeled, 100-ton omniMove AGV, designed for a major OEM, carries and lifts airframe wings into place for assembly with a fuselage. Source | KUKA

The RAMP equipment consists of a standard robot with an end effector that positions the material, and a comprehensive software suite capable of providing six degrees of freedom. The end-effector carries a deposition head with advanced thermal management technology for processing high-performance carbon fiber-reinforced thermoplastics.

Bheda says his company is working on extending the software to construct a system with multiple robots, the benefit of which would be two-fold. First, two or more robots could increase the throughput of the process, with one robot depositing the material and the other robot holding the part — which, additionally, provides more flexibility in positioning of the part, thereby widening the scope of complex shapes. Second, multiple robots would increase fiber orientation options and, thus, expand the potential for further strengthening the part. The RAMP software also is scalable for larger robots and larger parts.

The brains behind the robots

Robots, however, are only as good as the software that drives them. And software for robots differs from the software that drives CNC systems. Bheda, in fact, says Arevo's RAMP platform represents a *paradigm shift* in the way software can be developed and applied to competitive additive manufacturing technology.

Mathew Nalbandian, marketing and media director for Hypertherm Robotic Software, agrees, pointing out that programming software for robots is made uniquely complex by four factors: "singularity, collisions, reach limitations and motion granularity."

In mathematics, a *singularity* is a point at which a function takes an infinite value. A robot singularity occurs when robot axes are aligned or redundant — in other words, when a robot is trying to go to a designated point but encounters an infinite number of solutions, which can cause unpredictable robot motion and velocities.

Collisions are difficult to foresee when a robot will be moving around a complex path. To protect against this risk, Hypertherm's Robotmaster, for example replicates the actual workspace environment in its simulator, allowing the user to detect and avoid potential collisions.

The software must also account for *reach limitations*, any point in the process that the robot's end effector, simply due to physical obstacle or lack of robot arm length, cannot access.

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Read more about the early work by Electroimpact and others on AFP and ATL machinery in "ATL and AFP: Defining the megatrends in composite aerostructures" | short.compositesworld.com/1CNvo7EI

Read more about the Automated Composite Structure Inspection System online in "NCDMM, Ingersoll, Orbital ATK complete automated composites inspection system" | short.compositesworld.com/ACSIS

Not so self-explanatory is *motion granularity*. Robots move in a manner that is very different from the movement of CNC machine tools. One example is that robots are designed to perform in the optimal cycle time: A robotic system will typically *compromise the shape* of the programmed path by, for example, rounding a square corner to achieve the shortest possible elapsed time. This is not generally acceptable in modern aerospace applications, which require precise execution of programmed paths. Robotmaster, therefore, offers unique tools for optimizing robot playback of programs and for setting motion parameters that are most suitable for high-accuracy applications.

Nalbandian says aerospace companies now use Hypertherm's Robotmaster software to program their robots for the making of landing gear, fuselages, window frames, interior components, trimming of airplane skins and painting of the aircraft, as well as composite trimming, drilling and riveting. "Robotmaster software streamlines programming, simulation, code generation and path optimization into one integrated solution," he maintains.

Pluses outweigh minuses

Implementation of robotics in aerocomposites manufacture still poses challenges. The biggest appear to be in meeting requisite tight tolerances and precision placement standards on very large parts, such as fuselage components, during operations such as drilling and filling (with fasteners), composite layup, sealing and dispensing. These difficulties are being resolved by R&D involving high-powered vision systems and metrology technologies capable of more precise measurement and alignment during assembly of large parts, such as wings onto fuselage sections. Laser technology for measurement and scanning also is advancing.

That said, robots can perform complex tasks with extremely high repeatability and improve throughput so that manufactured goods move through the factory faster and with greater efficiency. And, compared to large machine-tool production systems, such as gantry-based AFP systems, robotic systems can be commissioned at significantly lower total capital cost. Further, they can be applied to a wide range of repetitive and often physically difficult tasks, relieving technicians from work that is hard on their bodies, and thus prevent injuries.

Masinick concludes, "Aerospace is definitely a growth area for robotics. The OEMs are finally accepting robotic automation as the way to go and the robot companies are seeing in aerospace what we saw in automotive — a way to improve their process, improve their throughput, and improve their quality." CW

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Harris Corp., Rochester, NY, US

High-technology telescope and space structures expertise has its roots in legacy Kodak programs.

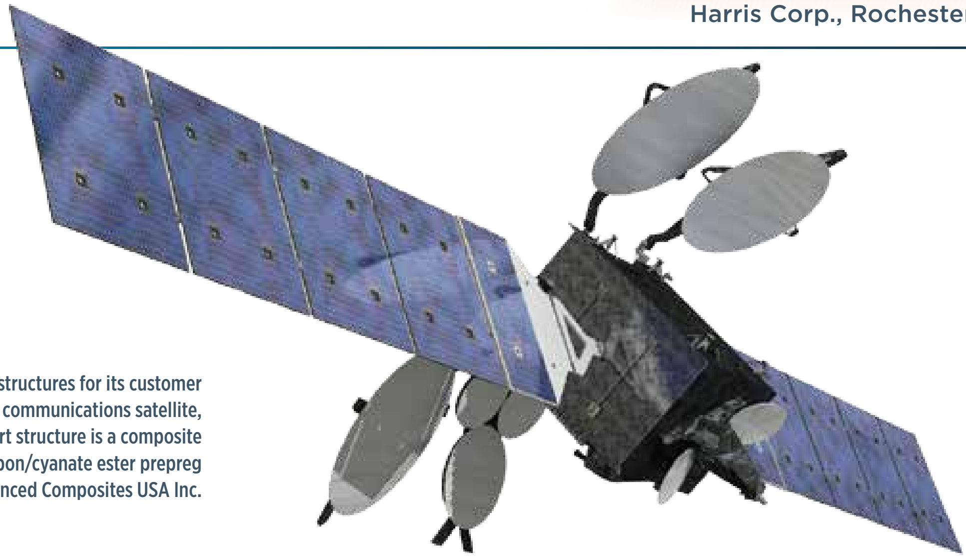
By Sara Black / Technical Editor

■ Harris Corp. acquired Exelis Inc. Geospatial Systems in 2015, and *CW* got the chance to tour the Geospatial Systems facility, located in Rochester, NY, US. Formerly part of camera and photographic film giant Kodak, the site helped pioneer satellite film surveillance technology and today continues to specialize in satellite and telescope structures.

Source (all photos) | Harris Corp.

» Flashback 55 years to May 1960: An American *U-2* spy plane, equipped with photographic equipment for taking high-resolution photos of the Soviet Union, is shot down by the Russians and its pilot, Francis Gary Powers, is captured. The incident creates a major foreign-policy headache for President Eisenhower and squelches a planned peace summit. Eisenhower orders an end to *U-2* overflights of the USSR shortly after the incident, but unbeknownst to most US citizens, new technology is already in place: The US government's Corona program reconnaissance satellites, equipped with powerful Kodak film, are already collecting images of the USSR for the US Central Intelligence Agency. The company behind the Brownie camera was in fact involved, via Corona, in top-secret photo technology that wasn't declassified until 1995.

Although those programs are long over, the Kodak group in Rochester that was involved in those space reconnaissance programs was eventually spun off and absorbed by ITT, which later became Exelis Inc. Geospatial Systems (McLean, VA, US). Exelis was acquired in 2015 by Harris Corp. (Melbourne, FL, US), a specialist in advanced electronics and communications technology. *CW* had the opportunity to tour the Harris facility in Rochester, with Joe Phillips, the director of Harris' Precision Structures group, and Irene



Harris produces the bus structures for its customer Orbital ATK's GEOStar-3 communications satellite, shown here. The central support structure is a composite made with high-modulus carbon/cyanate ester prepreg supplied by TenCate Advanced Composites USA Inc.

Lockwood, a communications manager at Harris, as guides, to see satellite production first-hand.

Engineered, and tested, for space

Phillips directs a sizeable workforce that is currently designing, fabricating and testing stability-critical telescope structures as well as other customer projects, including GEOStar-3 communications satellite bus structures for customer Orbital ATK (Dulles, VA, US), in a carefully controlled systems-engineering process: "We build to spec as well as to print, depending on the customer," he says. The group includes nearly 50 engineers, including specialists in dynamics, thermal performance, materials, structures, electrical and process engineering, as well as industrial engineering. Analysis and design software used by the engineering staff includes Nastran from NEI Software (Westminster, CA, US), Patran from MSC Software (Newport Beach, CA, US) and Pro/Engineer (now PTC Creo Parametric) from PTC (Needham, MA, US). Although it is related to the Harris (former Exelis) facility in Salt Lake City, UT, US, Phillips clarifies that the Salt Lake City group is involved in high-volume manufacturing, primarily on the commercial aircraft side, while in Rochester, "we design, analyze, fabricate and test custom solutions where the volumes are typically one to five units. Our quality management system is certified to AS9100."

The tour actually begins near the *end* of the process, in the environmental testing laboratory, which Phillips says represents a "big part" of his group's efforts. There, a completed "thrust tube," or composite cylinder, approximately 3m tall,1.3m in diameter and built to support the propulsion system for an 8-kW communications satellite, is mounted in a static load test tower in preparation for tests that simulate launch loads, to demonstrate workmanship and part acceptance for customers. The group produces the thrust tubes in a variety of diameters (all about 3m long) specific to each customer's project. They act as a satellite's backbone, explains Phillips, to which fuel and oxygen tanks, electrical boxes, antennae and much more are attached.

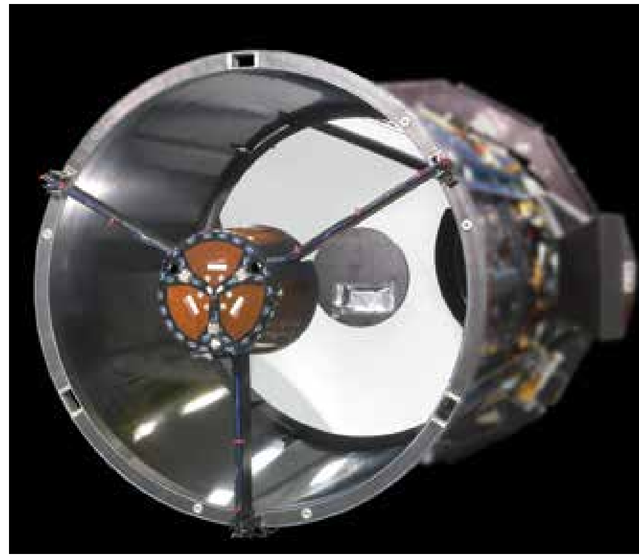
The testing laboratory is equipped to record strain data on 380 channels, 32 channels of acoustic emissions and has available 32 linear variable displacement transducers (LVDTs) to measure the smallest movements or displacements in the structure, with testing load control provided by software from MTS Systems Corp. (Eden Prairie, MN, US). The lab also is equipped with a horizontal and vertical shaker, located in a Class 10,000 cleanroom, for tests that require contamination control.

"We've been producing optical systems for more than 50 years here," says Phillips. "Think of satellite images you see on TV or online, or space telescopes — thermal and dynamic stability is critical to maintaining focus and pointing, which is validated by extensive testing."

Tests for composite workmanship also include thermal cycling in vacuum and under ambient conditions, in temperature-controlled chambers, and during acoustic tests, vibration tests, and modal-excitation tests, which determine the harmonics generated during excitation on a shaker table. Phillips explains »

A nearly complete GeoEye satellite structure is shown in the integration facility of the High Bay area. The structure is encased in its multi-layer insulation (MLI), consisting of multiple layers of Kapton, a polyimide with good ultraviolet radiation resistance.

■ Harris relies on high-accuracy, 5-axis CNC machining centers such as this one from Diversified Machine Systems (DMS), one of several the company employs for both composites and metals, in support of critical part fabrication for its satellite structures.



■ Harris' 1.1m commercial imaging telescope is shown here. The composite telescope structures are designed to have zero CTE (coefficient of thermal expansion) and near-zero CME (coefficient of moisture expansion), and are made with a proprietary hybrid laminate that combines two different fibers to optimize performance.

the modal data are correlated with finite element analysis (FEA) to ensure that no harmful or even destructive modes occur during launch and operation. For static testing, a load test tower dotted with hundreds of tapped holes allows for rapid setup of customized load trains for any size part, with load actuators situated in any orientation. "Our flexible test tower and standard load trains allow our engineers to quickly design a test to simulate launch conditions while minimizing the number of configurations required to fully exercise the structure," asserts Phillips. He also points out an "Iron bird" test in progress on one test stand, which refers to a steel dummy part that is tested first, at twice the maximum load, to ensure that the test equipment itself is operating optimally before the costly composite part is tested. And, he describes additional laboratory space that houses a complete composite material characterization lab, for coupon testing in accordance with ASTM International standards.

More testing is conducted in the mechanics calibration and measurement (MCM) laboratory next door, which houses a Summit coordinate measuring machine (CMM) supplied by View Micro-Metrology (Tempe, AZ, US). Phillips describes how tubular composite strut structures, used for secondary mirror supports, are tested in the MCM Lab: "We bag the part, then immerse it in a tube of water, and the water is slowly heated. A laser interferometer device, a precision measuring system for motion, detects any growth in the tube due to thermal expansion." The coefficient of thermal expansion (CTE) acceptance for carbon composite struts, every one of which is tested, is 0 ±0.08 ppm/^{0}F**.** He goes on to say that for years, Invar was used for certain structural elements, for its very low CTE and good stability. But, the group transitioned to zero-CTE carbon/epoxy materials to add weight savings in the 1980s: "Our niche is really understanding the properties of a wide variety of materials, composite and metal, and their performance in the space environment, and how to select the best materials to support specific payloads," adds Phillips.

Precise optical structures and composite supports

Before getting into details of actual composite fabrication, Phillips first shows *CW* how the optical mirror systems, which eventually are mounted within the composite thrust tube structural supports, are produced and tested. In this area, booties, hair nets and lab coats are required, along with safety glasses. Called the High Bay, the room contains eight enormous optical test chambers, 11m in diameter and 21m tall, around which the building was originally constructed. These chambers, equipped with support frames for the tested assemblies, simulate deep space conditions. Hard vacuum and large radiators produce high heat; intense cold is generated via liquid nitrogen. Each chamber "floats" on supports that completely isolate it from any vibration generated within the factory during tests. "Even fluorescent lights can affect a test, since they operate at 60 Hz and create slight vibration," says Phillips.

The chambers are used to test and validate the optical performance of the mirrors used in optical telescope assemblies for Earth observation and other applications. Mirrors are produced from ultra-low expansion (ULE) glass blanks made by Corning Inc. (Corning, NY, US). The "boules" or blanks used to fabricate the mirror's honeycomb-shaped core are first waterjet cut to approximate shape. Additional glass boules, used to form the facesheets, are ground and shaped prior to joining to the core, then are carefully polished using several methods. The final glass figure is achieved with an argon laser in a process called *ion figuring*; the laser beam shapes and polishes the glass surface at the molecular level, producing a high-precision surface. "Our FEA models predict the sag in the mirror's surface here at the facility, in Earth's gravity. The predicted displacements are subtracted from actual surface measurements and the delta becomes a hit map for the ion-figuring process to produce an optical surface that, when in orbit, assumes the correct shape in zero gravity," says Phillips. Kodak pioneered this ultra-precision mirror production process and the Rochester facility of Harris has supplied several major Earth observation imaging systems and sensors, including GeoEye-1 and WorldView-1, -2, -3 and -4.

At the other side of the large High Bay, in the integration facility, Phillips points out several optical telescopes that are undergoing assembly, with the addition of electronics, wiring and other necessary equipment in progress. He also notes the multi-layer insulation (MLI) materials, supplied by Sheldahl (Northfield, MN, US), that line the telescope's outer surfaces —15 to 25 layers of aluminized Kapton (a polyimide with good ultraviolet radiation resistance), with each layer separated by polyethylene scrims (see photo at bottom of p. 49). The telescopes are designed to maintain positive thermal control by cold-biasing the system and adding heat via Kapton heaters, Phillips says.

This photo demonstrates how the tubular carbon composite struts, a Harris specialty, are used to support the elements of a telescope, in "bi-pod pairs." Kinematic mounts minimize strain, and the struts control each degree of freedom for maximum stability. The composite materials exhibit zero CTE.

To support the optics, however, composite structure is a necessity. The tour proceeds on to the Low Bay portion of the building, which houses composites manufacturing, all of which is hand layup. Phillips shows a fabrication area where large (2.5m by 7m and 2.5m by 4m) heated platen presses produce the flat honeycomb panels, typically about 12.5 mm thick, that surround a thrust tube to create complete satellite bus structures and other satellite components. Core is typically aluminum honeycomb with skins of out-of-autoclave cure-capable, high-modulus M55J carbon/RS3C cyanate ester prepreg supplied by TenCate Advanced Composites USA Inc. – Fairfield (Fairfield, CA, US). Phillips explains that the heated platens also are used to consolidate radiator panels, which contain embedded heat pipes filled with ammonia that act to dissipate heat generated by spacecraft components. "The liquid ammonia flows to the hot spot via capillary action. As it absorbs heat, it vaporizes and travels back to the cold spot via the center » of the tube, where it condenses and the process repeats. It's a passive radiator or heat exchanger that keeps the electronics and optics from overheating."

Next, Phillips and Lockwood show where the cylindrical thrust tubes, described above in the environmental test laboratory, are fabricated and incorporated into the satellite structures. Again, TenCate's high-modulus M55J carbon/RS3C cyanate ester unidirectional prepreg is used to produce what appears to be absolutely flawless laminates. To assemble the bus structure, a master assembly tool (MAT) is used to hold each element in place during match bonding, including the radiator panels. The wheeled thrust tube mandrel can be easily rotated to facilitate layup, and transfers parts to the adjacent 5-axis machining center for required machining to accommodate the many attachment points to which satellite elements must be affixed.

In another fabrication area, we see technicians lay up curved radio frequency dishes for a proprietary program, using sandwich construction. Dish-shaped male molds are supplied by Lynco Grinding Co. Inc. (Bell Gardens, CA, US), although Phillips says that Harris is starting to fabricate select layup tools in house. The material selection, tool design and processes selected to fabricate the reflectors are critical factors that must be considered in order to meet operational performance requirements, explains Phillips.

Harris is well known for its tubular struts, used in many applications (e.g., to support the secondary mirror in a satellite optical system; see the photo on p. 51). Phillips explains that the struts are frequently deployed in three "bi-pod pairs," which controls each degree of freedom of the mounted component. The kinematic mount minimizes mount strain and environmentally induced thermal strain due to varying temperatures and material properties. The proprietary composite tubes, ranging from 6.5-mm to 200-mm inside diameter, are produced on metal mandrels, says Phillips, "The fibers and resin are blended in a way that results in a zero-CTE laminate with a modulus as high as 62 Msi in the axial direction."

A digital factory, with continuous improvement

At this point, the tour passes through a quality control area, and Phillips pauses to describe the "digital factory" procedures that have been put in place, including ubiquitous bar coding on all materials and parts, electronic work instructions (EWI) and the linking of CAD files to technician's actions on the factory floor that "have improved our manufacturing processes and speed." Using adhesive mixing as an example, which is an important part of the group's cored composite panel-fabrication process, he relates that all steps of mixing are now better controlled, from selecting the correct (bar-coded) adhesive for a particular task, to the mixing process itself; three planetary mixers from Thinky USA (Laguna Hills, CA, US) are employed to provide more consistent blending and better air elimination, improving adhesive performance. All adhesive bonds, he adds, are tested as part of the quality control process, using single lapshear coupon testing, per ASTM standards.

Throughout the rest of the Low Bay facility, Phillips points out the sheet metal fabrication area and machine shop for metal fab, which includes a Summit (Oklahoma City, OK, US) milling machine equipped with vacuum, and a 1.85m by 3.7m by 4.3m work envelope, and a five-axis CNC machining center from Diversified Machine Systems (DMS, Colorado Springs, CO, US). Two autoclaves from ASC Process Systems (Valencia, CA, US), 1.2m by 1.85m and 1.85m by 3.7m, are available, as is an adhesive film reticulator, a machine that deposits an adhesive film only along the cell edges of honeycomb core, prior to facesheet bonding. In a material prep area, an Eastman Machine Co. (Buffalo, NY, US) automated cutting table "has improved our efficiency tremendously," states Phillips. Debulk tables, a bagging area and a freezer for prepregs are part of the material handling area (two freezers are located off site, as well).

As our tour ends, Lockwood notes that Harris technology has been on every US global positioning system (GPS) satellite ever launched, and the company is involved with weather monitoring and forecasting programs, NASA communication networks for satellite tracking, and the James Webb Telescope. And space applications aren't the only projects Harris handles. Recent solutions under "other" include a large, ground-based radar structure that had challenging stability and weight requirements given the harsh operational environments. Another is a composite inspection machine for a computer chip manufacturer in California that required rapid movement, at high production speeds, but very accurate dynamic control.

Concludes Phillips, "We're in a unique position, with our history, materials knowledge and capabilities, and our engineering staff, that allows us to produce key systems for many customers where strength and stability are critical." The company's rich legacy, coupled with its composites expertise, promises a successful future. CW

LEARN MORE

Read this article online | short.compositesworld.com/Harris

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Production mandrels for a cryotank's fluted-core skirt

Following up on the CCTD program's 5.5m cryotank skirt's fluted-core design activities (covered in *CW's* February issue), this NASA-funded SBIR program produced a 2m by 2.5m arc section panel to demonstrate the technical feasibility of Spintech LLC's Smart Tooling approach for highly loaded launch vehicle structures.

Source (top right) | NASA

Source (left, lower left) | Boeing

"Smart tooling" cuts time and risk for complex unitized composite structures production

One-piece bladder tooling helps to actualize NASA/Boeing's revolutionary fluted core design for next-gen cryogenic fuel tank skirt.

By Ginger Gardiner / Senior Editor

» In February, *CW's* Focus on Design feature reported on the Composite Cryotank Technologies and Demonstration (CCTD) project's successful build of a subscale 5.5m-diameter composite tank with special attention to the makeup of its carbon fiber-reinforced plastic (CFRP) fluted core skirt structure (see Learn More on p. 60). Although the skirt's all-new structural scheme was an unqualified improvement over previous honeycomb-cored sandwich skirt constructions, the CCTD team knew the rigid trapezoidal mandrels used to mold the skirt prototype's core would not be practical for use in a production skirt for a tank that would fly on a launch vehicle.

In that scenario, explains Tom Margraf, the director of engineering for tooling technology innovator Spintech LLC (Xenia, OH, US), "the final cryotank skirt components will have to assemble to other pieces." In order to accommodate them, the skirt's flutes must *taper* at the structure's open ends. "Each section's flutes will have to narrow in cross-section to receive a coupling collar," he explains. Thus narrowed

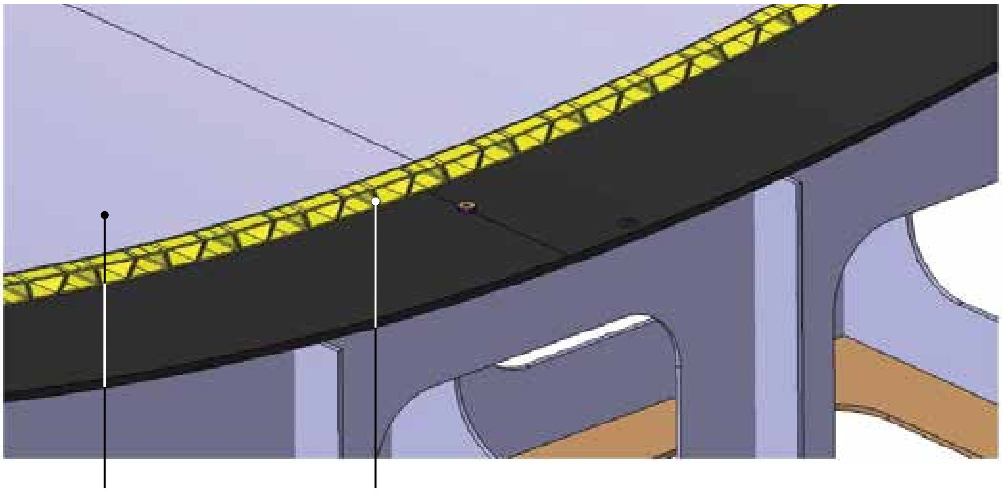
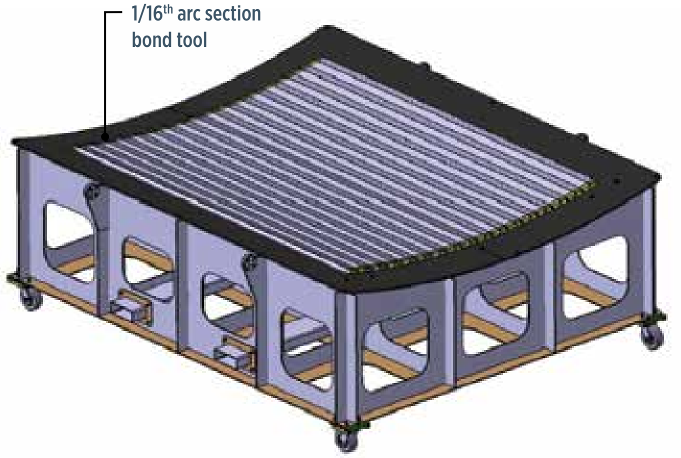


FIG. 1 **Co-cured inner and outer skin and fluted core**

The SBIR program proposed placing prepreg wrapped flute tools — Spintech's Smart Bladders — onto a bottom skin layed up on a NASA-supplied arc-shaped outer mold line (OML) cure tool. After applying the top skin onto the flutes, the arc section then would be autoclave-cured to form a unitized structure.

Source | Spintech LLC



during manufacture, then cured, the flute's ends would prevent mandrel removal. As a next step, then, CCTD's team of NASA and Boeing Co. (Chicago, IL, US) engineers worked with Spintech to demonstrate how the latter's Smart Tooling products could provide a solution to this problem.

NASA funded a Small Business Innovative Research (SBIR) program, using CCTD's 5.5m skirt design as a baseline geometry, with two main objectives: Demonstrate the technical feasibility of a Smart Tooling product on a NASA launch vehicle component, and evaluate the performance of Smart Tooling in comparison to the component's baseline tooling methodology. To secure those objectives, Spintech made 27 3m-long mandrels, trapezoidal in cross-section, called Smart Bladders, which Boeing then used to mold a 2m-by-2.5m fluted-core skirt/cryotank arc-section panel.

Requirements for fluted core tooling

The fluted-core construction used in the CCTD project was created by wrapping four-ply stacks of prepreg around long, thin mandrels with trapezoidal cross sections, arranging these layups on a faceskin layup, topping them with another faceskin layup and then curing the result as a unitized skin/fluted-core structure in an autoclave. The wrapped trapezoidal tools were alternated — wide end facing out/wide end facing in — to achieve the nesting that creates the truss-like core structures.

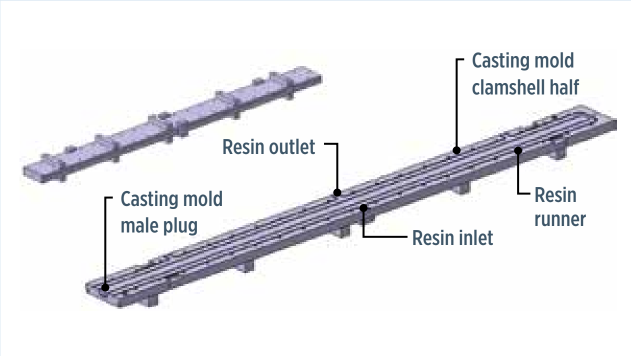
Production-worthy mandrels would need to be stiff enough at room temperature, during and after layup, to allow hand carry without flexing significantly, which could induce wrinkles. They also would have to have sufficient compressive strength to resist automated flute-wrapping techniques and, eventually, automated fiber placement (AFP) head pressure, yet be highly elastic during cure to translate sufficient internal force from the autoclave onto the wrapped layup radii, webs and caps. This would ensure full compaction with minimal voids. Further, the tooling had to yield a part with consistent web, skin and radius dimensions — the flute walls and skins could not bulge (exhibit concavity/convexity).

After cure, the mandrels had to release from the flute inner walls and then be pulled or pushed out of the cavity with minimal force. Further, the mandrel materials had to withstand multiple cure cycles with limited refurbishment, and tool cost must be reasonable vs. other tooling approaches. Finally, the mandrels had to be scalable from the 3m lengths that would be used in this SBIR skirt arc test section to the roughly 30m lengths envisioned for next-generation launch vehicle cryotank skirt structures.

Dynamic modulus polymer tooling

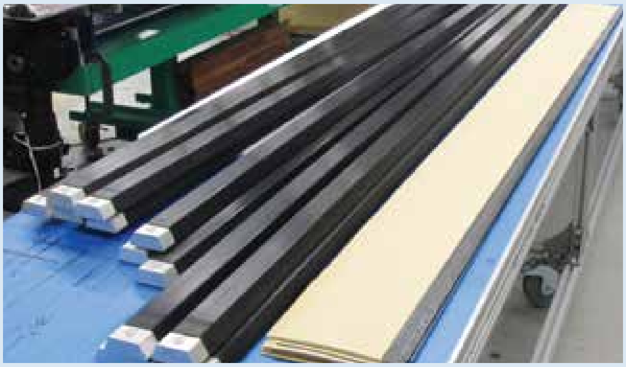
Spintech's patented Smart Tooling products are based on a class of thermoset materials called shape memory polymers (SMP). These are dynamic-modulus materials that respond to temperature. For example, an epoxy-based SMP can exhibit properties similar to common epoxy resins up to 80°C, but then transition from a rigid to an elastic material in the 80-105°C range, and become fully elastomeric above 105°C, achieving strains up to 400% (neat polymer).

Smart Tooling replaces the metal mandrel with the Smart Bladder, a hollow SMP tube that is pre-formed to the part's inner trapezoidal mold line. The Smart Bladder is rigid at room temperature, but becomes a balloon-like elastomer during cure, capable of translating internal cavity pressure from either the autoclave or a separate pressure system (e.g., a compressor or gas bottle) — and »



1 The Smart Bladders must first be formed into their basic hollow configurations. This is done in a special mold depicted in the illustration at left. Proprietary reinforcement was layed onto a male mandrel, which is placed into the female clamshell mold. The shape memory polymer (SMP) resin was injected into the closed mold and cured to cast each Smart Bladder. **Source | Spintech LLC**

2 The basic Smart Bladder blanks, however, then must be formed to final part tolerance. That is accomplished in this second metal mold set, which is machined to the flute inside mold line (IML) tolerances. There, the blank's SMP material was conformed to the mold's dimensions using pressurized air and heat — a shape it would hold once cooled again to room temperature. (This two-step forming process permits the use of a single mandrel and two-part female mold to form hollow bladders that then could be adapted to a variety of differently shaped parts.) This second mold would also be used to reset the Smart Bladders' IML shape between part cure cycles, after the SMP material's IML shape was "relaxed" to enable easy removal from the flutes. **Source | Spintech LLC**



3 The Smart Bladders, after removal from the second mold are shown here, shaped precisely to the flute's IML and fitted with end caps. **Source | Boeing**

4 Four plies of CYCOM 5320-1 carbon fiber/epoxy prepreg were layed, each ply offset by 7.6 mm, to create a staggered joint in the final flute. These stepped plies were debulked into a stack called a charge. **Source | Boeing**

5 Each carbon fiber prepreg charge (black line in center) was wrapped around a Smart Bladder (off-white line next to prepreg) and tamped down by an automated machine to create a pre-compacted flute preform. Source | Boeing

6 To fill the small gaps between the slightly radiused top edges of the bladder-supported layups between the flutes and the skirt's top and bottom skins, pultruded radius fillers (or "noodles," see inset) were produced by pulling multiple slit tape carbon fiber tows through a heated die, where they were compacted and cured to the desired shape. Source | Boeing / (inset) Spintech LLC

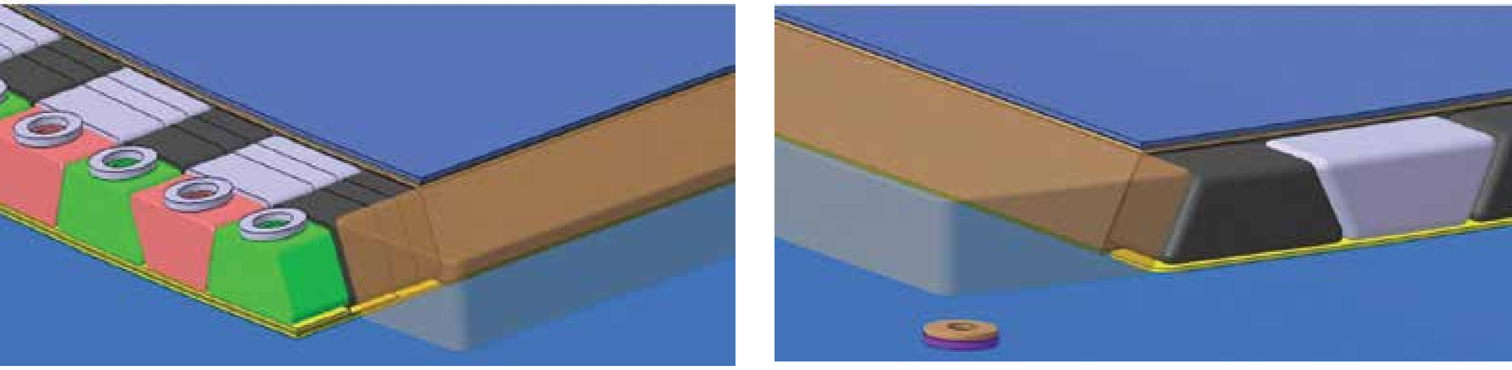
9 After debulking, the top/inner skin was placed and debulked, and the whole assembly (shown here) was prepared for autoclave cure, with each Smart Bladder individually vented, via the end cap shown in Fig. 2, through the vacuum bag. Source | Boeing

7 Technicians collected the layed up smart bladders (alternating wide end in/wide end out) in sets of eight or nine, debulked them under a vacuum bag to create a flute pack, then began laying in the radius fillers, as shown here. (This pack is shown from the end that clearly shows the perpendicular closure illustrated in Fig. 2, p. 58.) Source | Boeing

10 The vacuum-bagged, fluted arc panel was then wheeled into this autoclave for cure at 121°C for 4 hours. Source | Boeing

8 A flute preform pack is shown here with all the pultruded radius fillers in place between them. This and the other fully kitted flutes were then debulked onto the arc section bottom/outer skin. Source | Boeing

11 After cure, the arc panel was heated above 62°C in a standard convection oven, enabling extraction of the softened Smart Bladders by hand. Source | Boeing



can withstand up to 191°C. Thus, Smart Bladders act as a rigid layup mandrel at room temperature, but can function at elevated temperatures as a bladder to consolidate the laminate from the inside out and to facilitate removal.

"This technology originated from an SBIR targeting the F-35 composite inlet duct, which required very tight control of the inner mold line," recalls Margraf. "The Smart Tooling material's ability to transition from *rigid* during lay-up to *elastomeric* during cure, and consolidate against an outer mold line rigid tool surface, found strong market acceptance in components that were traditionally bladder molded, like blade spars," he adds.

Margraf explains that the typical solution for this type of problem is to lay up the part onto a multi-piece metal mandrel and place that inside a two-piece, machined female cavity mold. "Now you must go in and disassemble the metal layup mandrel and replace that with a vacuum bag so that you can achieve compaction on the interior surface," he adds, because the metal mandrel will act as a heat sink and could cause thermal non-uniformities that reduce residual stress within the part. "Not only is this labor-intensive, it also risks damage to the layup during removal of the steel mandrel and insertion of the vacuum bag."

"The Smart Bladder is a layup tool that *does not have to be removed* prior to autoclave cure, but instead exerts compaction pressure on the part like a vacuum bag does," says Margraf. "Because we relax the Smart Bladder for easy extraction after cure, we then reform it between cycles to the net inner mold line of the part, using a reasonably priced metal mold."

Margraf notes that Smart Tooling excels with parts that have line-of-sight issues for extraction, meaning they are curved so that you cannot pull a metal mandrel out without disassembling it. "Our material is elastomeric, so you are essentially pulling out a rubber hose which has no clearance issues with the part."

Demonstrating fluted core production

Boeing provided the flute design for the 5.5m cryotank and NASA Marshall Space Flight Center (Huntsville, AL, US) supplied the composite outer mold line (OML) cure mold for the tank arc section (see Fig. 1, p. 55). Spintech then began manufacture of the Smart Bladders, one at a time, with a single set of matched steel clamshell molds (see Step 1, p. 52). Proprietary reinforcement, which increases Smart Tool toughness but still allows for elastomeric expansion, was placed onto a male mandrel, which was then placed into a female clamshell mold. The clamshell mold was closed and SMP resin was injected and cured to cast a simple, hollow "blank" for each Smart Bladder. The final shape for each Smart Bladder would be imparted later.

FIG. 2 More than a mere mandrel

Each Smart Bladder would be cast with a perpendicular closure on one end (above) and after the casting mandrel was extracted, a metallic end cap would be bonded into the other end (left), to permit the hollow tool to be pressurized when it entered its elastomeric phase at high temperature while in the autoclave, to aid in compacting and consolidating the flute laminate from the inside while the vacuum bag compacted the layup from the outside. Source | Spintech LLC

In order to create a sealed cavity, each Smart Bladder blank was cast with a perpendicular closure on one end, and a metallic end cap was bonded into the other end after the metal mandrel for casting was extracted (see Fig. 2, above). The end caps will permit pressurization of the Smart Bladder in its heat-induced elastomeric state during the cure cycle.

Each Smart Bladder blank was then placed into a second metal mold, machined to the net inner mold line (IML) tolerance of the flutes (Step 2). For this demonstration project, the second mold may have seemed unnecessary, but Boeing wanted to adhere to the actual production process. When used to produce a part with convex-to-concave cross-section changes or other line of sight issues, the simply shaped hollow Smart Bladder is placed inside the second mold and conformed using compressed air. Boeing used this process in the SBIR program, heat-forming each Smart Bladder to its final shape. This same forming mold was also used after each cure cycle to reset the IML flute tolerances of the Smart Bladders, ensuring proper layup geometry for subsequent parts.

Plies of CYCOM 5320-1 carbon fiber/epoxy prepreg from Cytec Solvay Group (Woodland Park, NJ ,US) were cut with a 3-axis automated cutter and kitted. Four plies were then layed, each ply offset by 7.6-mm, to create a staggered joint in the final flute. These stepped plies were debulked into a stack called a charge (Step 3). Each charge was dropped into an automated machine and a Smart Bladder was placed on top. The machine then pushed the Smart Bladder and prepreg plies down into a female cavity. The wings of the prepreg (sized larger than the cavity) then stood up, extending beyond the tool cavity. The machine then lowered arms that folded these wings back onto the top side of the bladder, forming a flute. The machine then tamped down the completed layup, which resulted in a compacted flute preform (Step 4). Thus, the charge was wrapped very tightly around the Smart Bladder, and the stepped plies created the staggered joint that is preferred over a butt joint for load transfer. Sets of eight or nine flutes were then collected and debulked under a vacuum bag to create a flute pack (Step 5).

The debulked flute packs were then placed onto the bottom/outer skin layup, which already had been applied to the carbon composite arc section mold tool and debulked. Pultruded carbon fiber composite "noodles" were required to fill in gaps between the flutes. Multiple slit tape carbon fiber tows were pulled through a heated die and compacted into the required shape (Step 6). Once the radius fillers were placed between all of the flutes (Step 7), the top/inner skin was applied on top of the now smooth surface and debulked to compact it to the flute-radius filler assembly. The layup was then prepared with thermocouples and vacuum bag for autoclave cure (Step 8). Each Smart Bladder's end cap was individually vented through the vacuum bag to the autoclave atmosphere, which prevented them from crushing under the autoclave cure pressure (6 bar) and allowed for pressurization and compaction of the flute interiors (Step 9).

The arc panel was step-cured at 121°C for four hours under full vacuum (Step 10). After initial cure, the panel was heated above 62°C in a standard convection oven so that the mandrels were sufficiently flexible for extraction. The panel was removed from the oven and the bladders were extracted by hand (Step 11). After the Smart Bladders were extracted, a final free-standing post-cure at 177°C was conducted on the panel. Although a stepped cure process was used here, per NASA material and process specifications, Smart Bladders do not require a step-cure process and are compatible with cures up to 191°C.

Extending to fastener-free and low-volume primary structures

Boeing completed production of the arc panel in April 2015 and reported that the Smart Bladder tooling did successfully make a high-quality part, and allowed easy extraction through the end-fitting area. "The rigidity of the net-shaped bladders during layup and not having to remove them and insert a bag is key to a significant quality improvement because you're never shifting your laminate relative to the mandrel," says Margraf. "These cryotank shroud parts are highly compressively loaded so that 0° fiber orientation accuracy is critical."

Boeing has contracted with Spintech to supply Smart Bladders for fluted core panels in support of Boeing's manufacturing technology development and demonstration efforts for NASA. Margraf adds that the product is evolving as well. Although the arc section built in the program covered here showed no narrowing of the flute cross sections, Boeing and »

Spintech have since completed more complex skirt flute geometries, including unitized skin-flute structures with significant change in cross-section. "We are … demonstrating [its] compatibility with more complex flute designs that will provide a solution for trapped tooling with no line of sight for removal," he says.

Margraf notes that the fluted panels look a lot like unitized control-surface parts (skins with integrated omega stringers) that Spintech is also heavily supporting right now. "We can co-cure all of these layups together in a single cycle because we are able to exert consolidation pressure on all composite surfaces, whereas the baseline process can only exert pressure in one direction," he explains. "So now you can, theoretically, get rid of chicken rivets." Margraf cites Spirit AeroSystems' (Wichita, KS, US) Inflexion technology as an example, developed to produce fully integrated composite fuselage modules (see Learn More). "That is one of the end games for our products," he points out. "We can deliver solutions for manufacturing fully unitized structures that do not require any secondary bonding or fastening."

Spintech is working with a variety of partners to push this technology, and has already deployed unitized-structure tooling solutions in markets with less onerous certification requirements. "One of our customers told us their manufacturing process, including trimming, assembly, bonding and fastening, used to take a month per part," says Margraf, but he claims, "They can now do it as a single cured part in a week." (For other molding applications, see Learn More.)

Having attained a manufacturing readiness level (MRL) of 10 and technology readiness level (TRL) of 9 via previous programs and the successful demonstration in the Boeing/NASA fluted core SBIR program, Smart Bladders are now validated as a solution for volume production. Innovative technologies like these offer a welcome solution to an industry that needs to relentlessly pursue reductions in manufacturing cost and time that do not sacrifice quality in primary composite structures. CW

LEARN MORE

Read this article online | short.compositesworld.com/IM-FlutCor

Read more about Spirit AeroSystems' Inflexion technology in "Inflexion technology enables complex composite structures without fasteners" online | short.compositesworld.com/inflexion

Read more online about Smart Tool applications in "Caul plates get schooled as 'smart tools'" | short.compositesworld.com/smartcaul

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Composites Events

March 3-4, 2016 — Prague, Czech Republic
13th World Pultrusion Conference
pultruders.com/en

March 6-10, 2016 — Vancouver, BC, Canada
NACE Corrosion 2016
nacecorrosion.org

March 7, 2016 — Paris, France
SAMPE Europe Summit 2016 Paris
sampe-europe.org

March 7-9, 2016 — Beverly Hills, CA, US
***SpeedNews* 30th Annual Commercial Aviation Industry Suppliers Conference**
speednews.com/commercial-aviation-industry-suppliers-conference

March 8-10, 2016 — Paris-Nord Villepinte, France
JEC World 2016
jeccomposites.com

March 20-24, 2016 — Grapevine, TX, US
2016 No-Dig Show
nodigshow.com

CW March 29-31, 2016 — New Orleans, LA, US
Molding 2016
short.moldmakingtechnology.com/Molding16

April 5-6, 2016 — Hamburg, Germany
9th International Conference on Bio-Based Materials
biowerkstoff-kongress.de

April 5-7, 2016 — Hamburg, Germany
Aircraft Interiors Expo 2016
aircraftinteriorsexpo.com

April 12-14, 2016 — Detroit, MI, US
SAE 2016 World Congress
sae.org/congress

April 19-20, 2016 — Cleveland, OH, US
SPE Thermoset 2016 TOPCON
spetopcon.com

May 2-5, 2016 — New Orleans, LA, US
XPONENTIAL Unmanned Systems 2016
auvsishow.org/auvsi2016/public/enter.aspx#homeanchor

May 3-5, 2016 — Atlanta, GA, US
JEC Americas 2016/Techtextil North America
jeccomposites.com/events/jec-americas-2016-atlanta

May 11-13, 2016 — Shanghai, China
SAMPE China
sampe.org

May 16-19, 2016 — Orlando, FL, US
RAPID 2016
Rapid3devent.com

May 23-26, 2016 — Long Beach, CA, US
SAMPE Long Beach 2016
nasampe.org/events/event_details.asp?id=621205&group

May 23-26, 2016 — New Orleans, LA, US
Windpower 2016 Conference and Exhibition
windpowerexpo.org/wp16/index.aspx

CW June 15-16, 2016 — Novi, MI, US
ameri*mold* 2016
amerimoldexpo.com

CW June 15-16, 2016 — Novi, MI, US
Thermoplastic Composites Conference for Automotive (TCC Auto)
sstephenson@gardnerweb.com

June 15-16, 2016 — Stade, Germany
10th International CFK-Valley Stade Convention
cfk-convention.com

June 22-23, 2016 — Sheffield, UK
Composites Innovation 2016
compositesinnovation.com

July 11, 2016 — Farnborough, UK
Farnborough International Airshow 2016
farnborough.com

Aug. 28, 2016 — Gramado, Brazil
Brazilian Conference on Composite Materials (BCCM)
bccm.com.br/bccm3

Sept. 21-23, 2016 — Augsburg, Germany
Experience Composites
experience-composites.com/en

Sept. 26-29, 2016 — Anaheim, CA, US
CAMX – Composites and Advanced Materials Expo 2016
thecamx.org

SUPPLIERS TEAM TO AMP *VIKING 80C* PERFORMANCE

Weight is a key performance issue in large boats. Thanks to a coordinated effort with its fabric, core and panel suppliers, Viking Yachts was able to introduce carbon fiber cost-effectively, shaving weight and boosting speed in its new 24m-long *80C* model.

Source | Viking Yachts / Photo | Forest Johnson

A well-known builder of performance sportfishing and cruising vessels, Viking Yachts (New Gretna, NJ, US), partnered with key suppliers, **3A Composites** (High Point, NC, US), **Mahogany Co.** (Mays Landing, NJ, US) and **Vectorply** (Phenix City, AL, US), to replace fiberglass mat and woven roving with noncrimp fabrics in the 1990s, and to introduce infusion in the 2000s.

"We've worked with Viking for decades," recalls 3A Composites product development manager Russell Elkin, "but as a core supplier, you can't just recommend core, but must consider all of the materials in the laminate, because they all work together." Thus, when Viking began looking, again, to cut weight and boost performance across its models, it called on the same team to discuss options.

"The idea was to begin using carbon fiber," says Elkin, "but because it's more expensive, the question was where and how to employ it most efficiently." Reinforcements supplier Vectorply compiled initial material studies, using its proprietary VectorLam Cirrus software and suggested replacing typical but bulky 48-oz/yd^2 (1,628-g/m^2) and 64-oz/yd^2 (2,170-g/m^2) E-glass quadraxial fabrics with lighter 35-oz/yd^2 (1,187-g/m^2) and 44-oz/yd^2 (1,492-g/m^2) hybrid carbon/E-glass quads in selected laminates.

According to Viking Yachts' VP of design and engineering, Lonni Rutt, Viking's *80C* 80-ft/24m convertible (which offers an interior salon and more cabin space than Viking's express style) was the perfect model to trial the hybrids. "We were looking to bring a new model between the 76-ft [23m] and 82-ft [25m] class that was more efficient with better performance and more room," says Rutt. "Because we are limited in horsepower when you get to that size, performance is all about weight — a lighter boat is going to go faster."

The *Viking 80C* hull's reduced weight is the result of a team effort among Viking's suppliers.

Source | Viking Yachts

The suppliers worked together to complete several test matrices using the new materials, AME 6001 INF-35 vinyl ester infusion resin from **Ashland Performance Materials** (Columbus, OH, US) with Norox MCP-75 initiator from **United Initiators** (Elyria, OH, US). Testing was completed in November 2013, which included tensile, compressive, and flexural properties in the 0°, 90° and 45° (bias) orientations. Vectorply and 3A Composites then worked with Viking engineers to finalize *80C* hull bottom and side laminates, using ABS High Speed Craft scantling rules as guidelines. Samples of Vectorply EC-QXM 3508 and 4408 hybrid quadraxial fabrics were sent to Mahogany for cutting and kitting, then forwarded to Viking for in-house process testing.

Used in the *Viking 80C* and in the bulkheads for the larger *Viking 92* shown here, Mahogany Co.'s prefabricated composite sandwich panels with skins made from Vectorply E-glass fabrics and 3A Composites' PVC foam core reduce weight and boost performance.

Source | Mahogany Company and Viking Yachts

Mahogany pre-cuts and kits reinforcements and core materials for all Viking models. "We touch every composite part, from hulls and decks to stringers and bulkheads to floors and tanks," says Mahogany's VP of sales George P. Aaron. "Viking sends us the CAD files and we generate the kit patterns." He notes that with the large size of Viking's boats and backlog, the kitting provides needed production efficiency: "They receive a finished kit and can begin installation immediately."

The team worked to further minimize weight, optimizing the sandwich laminates for core density and thickness, according to loads and location. 3A's BALTEK SB.100 balsa is used in the hull bottom while lower density BALTEK SB.50 is used in the hull sides. The deck's sandwich construction is cored with a combination of BALTEK balsa and AIREX polyvinyl chloride (PVC) foam core.

Viking also incorporates sandwich panels for bulkheads and soles, cut to net shape and kitted by Mahogany, using 3A's AIREX C70.75 (75 kg/m^3) PVC foam core and Vectorply E-LTM 1208 glass fabric skins. These composite panels also help to keep weight in check.

Production of the first *80C* in early 2015 showed phenomenal results. Not only did it achieve a top speed of >41 knots — roughly 3.5 knots better than the 82-ft/25m boat — it also outpaced the smaller 76-ft/23m model. Rutt credits much of the success to team members. "A tremendous benefit for our company has been the specific knowledge everybody brings to the table," he says. "You collaborate with people who have the opportunity to see other things and bring new, different ideas." Elkin adds, "We were able to deliver a fully optimized composites package as a supplier team." CW

New Products

MRR Ultra Jet Black NCP Jet Black

» THERMOSET RESINS & ADHESIVES

Deep black gel coat

Ashland Performance Materials (Dublin, OH, US) is adding a new Maxguard MRR Ultra Jet Black gel coat to its existing line of high-performance marine products. Ultra Jet Black specialty marine gel coat joins the company's existing portfolio of products already available to boatbuilders for hull and superstructure finishes. It offers a deep color and "mirror-like" finish. Ashland says this gel coat was designed and formulated to provide boatbuilders with the deep black color they require to achieve the currently in-demand aesthetic among purchasers of new powerboats and yachts. In addition to its appearance and performance, Maxguard MRR Ultra is said to be easy to apply for manufacturers and has high-performing repair properties.
www.ashland.com

» PROCESS CONTROL/MONITORING SYSTEMS

Oven-cure airflow monitoring system

Wind-Probe LLC (Andover, MA, US) has developed an eight-channel, high-temperature airflow monitor, the Model 100, to assess the cure progress of carbon fiber composites in an oven environment. Wind-Probe says it has successfully demonstrated its prototype Model 100 in a customer oven, curing honeycomb core material blocks dipped in resin at temperatures as high as 191°C. The new system is designed to monitor airflow at rates ranging from 0 to 500 ft/min in curing ovens at temperatures up to 204°C. A production version of Model 100 is expected on the market later this year.
www.wind-probe.com

» ENVIRONMENTAL CONTROL TECHNOLOGY

Dust-collection shrouds

Clayton Assoc. Inc. (Lakewood, NJ, US) featured its new Clear Revolution line of drill and sanding shrouds, made from clear polycarbonate material and designed to capture 100% of produced dust, chips and particles. New to the Clear Revolution product lineup is a clear polycarbonate drill block (a device that prevents the drill bit from going beyond a certain depth) that is very effective in containing foreign object debris (FOD).
www.vacuumsanding.com

» MOLDING & FORMING EQUIPMENT

Hydraulic forming press

French Oil Mill Machinery Co. (Piqua, OH, US) and sister company **TMP** (Piqua), A Division of French, have developed a downacting sideplate hydraulic press that reportedly improves the quality of critical composite aerospace components while reducing production cost, energy consumption *and* noise. Designed with an Integrated RTM Package and Precision Control Motion Package, the press also includes French's patented tapered keys, designed to extend the life of the headblock, sideplates and main cylinder. The reservoir and hydraulic power are mounted on top of the headblock, reducing the overall press footprint. An integral platform with ladder allows access and serviceability. The energy-efficient hydraulic design is said to reduce horsepower and noise throughout the molding cycle. The press comes standard with steel, multi-zone, electrically heated platens rated to 260°C, with nickel-plated watercooling passages for corrosion resistance. Each platen includes edge insulation for enhanced temperature uniformity and provides three stages of cooling. Customers may upgrade to Uni-Temp platens for advanced heating/cooling temperature control and also may add the Edge II Control System, a specialized recipe and data-collection system programmed to monitor critical processing data and ensure consistent results. Customers can create and store process recipes, then capture, retrieve, and display data in chart/graph format on a color touchscreen interface. An Ethernet communication port permits integration into the customer's plant system, and French engineers can log into the permission-based control system remotely to upgrade software or troubleshoot systems.
www.frenchoil.com/hydraulic-press-design

» MAINTENANCE & REPAIR EQUIPMENT & SUPPLIES

Compact composites scarfing/sanding kit

Dark Matter Composites Ltd. (Redbourn, UK) has introduced DMP0111 Small Step Sanding Tool Kit, a composites repair system based on the company's established Step Sanding Tool Kits product. DMP011 can accommodate more complex composite repairs over much tighter curvature and more complex geometry using a smaller router with a smaller base and smaller diameter cutting heads. The kit accommodates repairs up to 300 mm in diameter in step increments as small as 1 mm and depth increments of 0.05 mm. Supplied with thin, flexible jigs and small-diameter planing heads to address intricate parts with tight internal and external curvature, the kit includes

- 44/60, 60/85 and 85/100 diamond grit surface planers in two diameters (set of six)
- Small circle jig for 10- to 150-mm diameter repair surfaces
- Thin and flexible, small-radius arm jigs for 100- to 305-mm-diameter repair surfaces
- Flexible large-radius arm jigs for 100- to 610-mm-diameter repair surfaces.

www.darkmattercomposites.co.uk

» NONDESTRUCTIVE EVALUATION TECHNOLOGY

Camera-based 3D measurement system

Imetrum Ltd. (Bristol, UK) has launched the Imetrum 3D Precision Displacement Tracker (PDT), which uses pre-calibrated stereoscopic video cameras, combined with Imetrum's patented Video Gauge software, to deliver reportedly precise noncontact measurements on any visible image point. 3D PDT eliminates the need to build frames for displacement sensors, bond strain gauges, run cabling or get too close to "hot" objects, saving time and improving the safety of test environments. The company says the system can take 3D displacement measurements at resolutions as fine as 0.5 μm, offering greater measurement precision and real-time measurement speed (up to 1000 Hz). www.imetrum.com

» THERMOSET RESINS & ADHESIVES

Industrial gel coat

Polynt Composites (Carpentersville, IL, US) has launched Polycor pre-accelerated industrial gel coat, based on orthophthalic unsaturated polyester resin, in spray and brush grades, formulated to provide an easy-to-sand surface that is highly resistant to micro-porosity. Said to be extremely sag-resistant, it is designed for parts that require paint and has the potential for use with internal composites where high UV- and water-resistance are not required. Polycor is available in white, off-white and pastel shades of gray. www.polynt.com/en

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Boat propellers with replaceable, interchangeable blades

Long glass fiber-reinforced polyamide makes this modular propeller tough enough for a challenging application, eliminating costly prop repair.

By Sara Black / Technical Editor

No-shop boat prop

Piranha Propellers (Jackson, CA, US) manufactures modular outboard motor boat propellers from injection molded, long glass fiber-reinforced polyamide. The unique composite props feature detachable, replaceable blades that are designed to break away if they strike an underwater object, without transmitting damaging loads to the propeller hub or outboard engine. Blade interchangeability and affordability save boat owners from those previous trips to "prop shops" for lengthy and expensive repairs to metal propellers.

Source | Piranha Propellers Australia

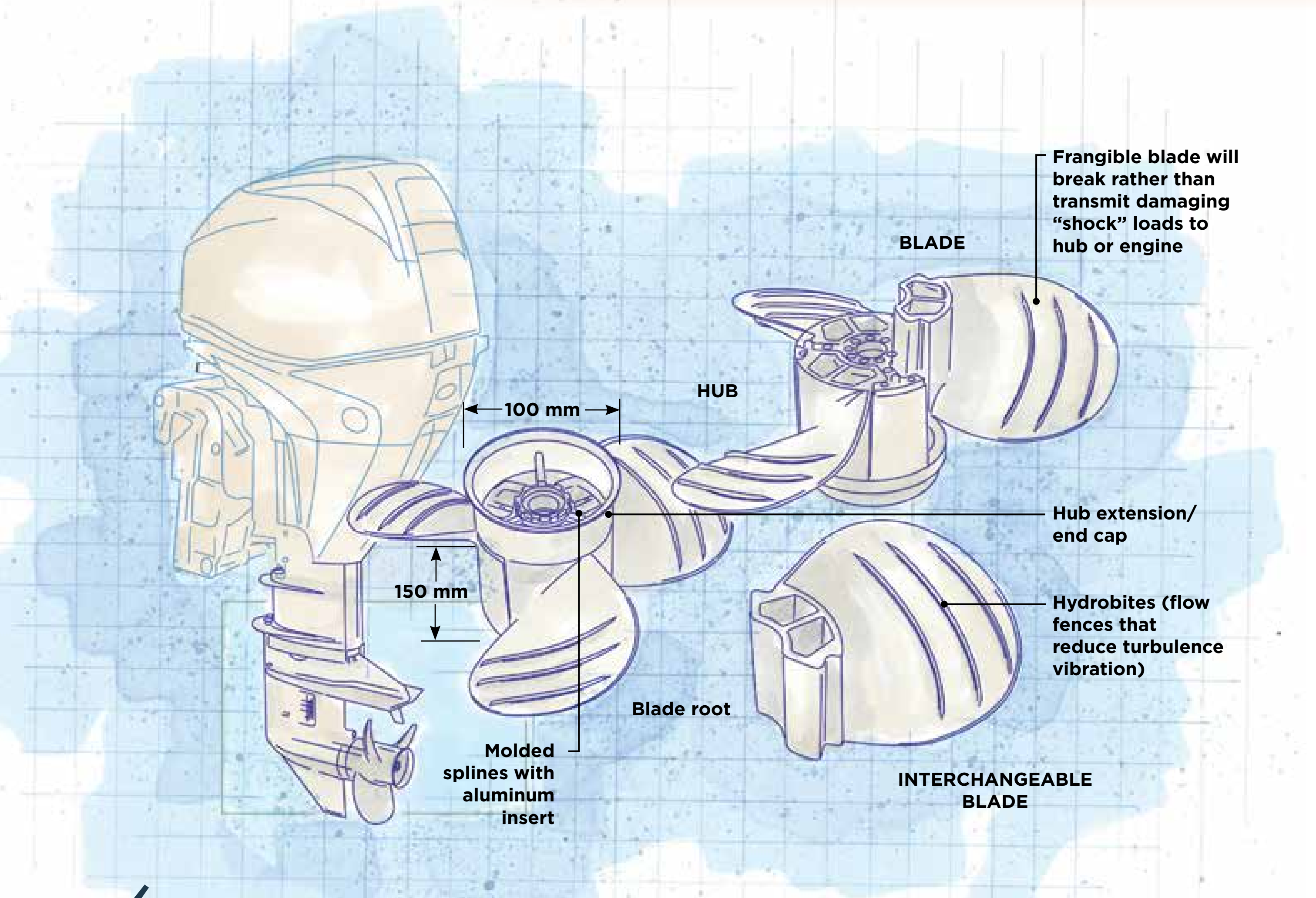
» Every motorboat owner has a tale of hitting a submerged obstacle or boat ramp and damaging a propeller. Typically metal, it must be removed and taken to a prop repair shop, then sandblasted, bent, welded and restored to original shape — a lengthy and expensive process. Brad Stahl, founder/owner of Piranha Propellers (Jackson, CA, US) and an aerospace engineer, says a conversation with his brother 25 years ago gave him an idea that is today reducing the cost of damage and eliminating those costly trips to the prop shop for his still growing customer base.

"At that time, I was working on an unmanned aerial vehicle project that was employing wooden propellers, and I wanted to find something lighter and less expensive. My search for composite materials brought me to long fiber-reinforced thermoplastics," recalls Stahl, "and I realized that they might work for a boat propeller." His work since then resulted in a propeller with a modular composite design, featuring quickly interchangeable blades, *and* a successful business manufacturing modular three- and four-bladed propellers for every major outboard motor.

The art of propeller design

Unlike ocean-going vessels, which travel at relatively low speed powered by large propellers (see Learn More, p. 63), faster, more mobile small boats depend on small props that turn at very high speeds, says Stahl. In water, that presents great challenges: "When I would design a propeller for an airplane, it was a straightforward problem. You know how they're going to work, plus or minus a few percent, and you're done. That's not the case with marine propellers." One reason is *cavitation*. As the curved blades turn through the water at increasing rotational speeds, the pressure on the low-pressure side of each blade drops below the water's vapor pressure (given the water temperature) causing *boiling* — the formation of millions of bubbles that degrade the flow regime. Further, says Stahl, the outboard's exhaust gases pass through the propeller hub, further degrading the flow, and the motor's lower unit, which sits below the waterline, also disturbs the water. The result? "It's a really messy flow environment that makes it impossible to perform CFD [computational fluid dynamics] or any kind of hydrodynamic analysis," says Stahl. "There are too many unknowns!"

He tackled the problem, nevertheless, envisioning a propeller with a 150-mm long, 100-mm diameter cylindrical hub with a central cavity that allows the propeller to slide over the outboard driveshaft, with three or four longitudinally shaped slots for inserting blade roots (see photo, above, and drawing, p. 61). A 75-mm long hub extension would fit on top, secured with a large nut that would grip splines molded in the central cavity and, when tightened, secure the blades in place. A series of successively larger hubs would be built to the boating industry's outboard motor size range (A, B, C, etc.), corresponding to horsepower rating. Each hub, then, could accept blades of different pitches, or degrees of curvature (in general, a higher pitch delivers greater thrust for a given horsepower). The parts would be injection molded with a fiber-reinforced thermoplastic. "I knew from my UAV work that glass-reinforced nylon could work, and would perform as well as metal in this application, at a more affordable price point," says Stahl. Stahl's target cost for a replacement blade was approximately US$25.



DESIGN RESULTS — Piranha Modular Propellers with Interchangeable Blades

- Modular design allows damaged blades to be extracted from the hub and replaced quickly, eliminating the costly and lengthy repairs required for one-piece metallic propellers.
- Blades are stronger than aluminum, yet exhibit a lower flexural modulus, which allows them to break under impact loads, avoiding damage to the hub and outboard motor drive.
- Long glass fiber-reinforced nylon, at nearly 60% fiber loading, has proprietary additives for greater impact toughness, vibration damping and temperature resistance to meet application requirements.

Illustration / **Karl Reque**

Stahl used software from NISA (Troy, MI, US) to conduct a structural analysis and develop a finite element (FE) model to understand how the modular prop blades and hub would behave under load. He assumed a 260-hp motor would deliver about 365 kg of thrust to the prop (typical for a small recreational boat), or 91 kg to each blade (assuming four blades), which helped him determine appropriate blade and hub material thicknesses. Blade shape was derived from aluminum props that had been proven in service. According to Stahl, "90% of the load on the blade is thrust, causing bending, which means that as the prop spins, the blade bends under the load."

Stahl's blades had to be thick enough to handle the thrust-induced bending loads, yet frangible enough to act sacrificially to save the hub and, in turn, the engine from damage given the unexpected, extra load of hitting a submerged object.

Initial molded prop blade prototypes were proof-tested concurrently with aluminum blades of similar shape, via static point bending tests in holding fixtures. The tests confirmed that the composite blades were stronger. But, as expected, the lighter composite blades lacked the stiffness (flexural modulus) of aluminum. To accommodate the bending that would occur under load, subsequent blades were overdesigned in terms of curvature: "I knew the flexural modulus properties of long-fiber composites when designing the propeller," said Stahl. "The molded part had to be slightly distorted so that when the blade is experiencing propulsion forces in the water, it would straighten and assume the proper shape to maximize thrust." The composite blade's lower shear strength compared to aluminum, also verified in testing, would enable the blade to absorb the energy from minor impacts, but break away and release energy under high impacts. »

Easy interchangeability facilitates performance flexibility

When a blade is damaged, it can be pulled out of the hub easily and replaced, as demonstrated here. Further, blades with different pitch can be interchanged to tune the propeller for an alternate performance regime. The co-molded aluminum insert inside the hub splines is just visible in the hub's top center opening. The hub extension/end cap is the piece on the left.

Source | Piranha Propellers Australia

A custom formulation for a custom component

The material used by Piranha to injection mold the propeller components is a custom, proprietary long glass fiber/nylon formulation developed for the company by PlastiComp Inc. (Winona, MN, US). Provided at fiber volumes up to 60% in 12-mm-long pellets, the material is enhanced with additives that give the finished part 40% more impact resistance and greater ductility. Carbon black content gives the material ultraviolet (UV) resistance, and additional additives give the part surface a semi-gloss finish. Source | PlastiComp

Tweaking material, updating designs

Stahl's first material choice was a standard 60% long glass fiber-reinforced nylon 6. He recalls that testing with higher horse-power motors was successful: The blade shape delivered thrust as predicted, and in strike tests, breakage occurred as desired. But testing also revealed that the reinforced nylon splines inside the hub could not handle the shear loads from the propeller input shaft: "The hub could handle the normal loads but not the shear when a strike would occur," he says. The solution was to co-mold a splined aluminum core insert inside the hub.

Material questions arose, however, when smaller propellers were tested on lower horsepower, two-stroke motors: Props were breaking under normal operating load. "We did a lot of testing," says Stahl, "and found the higher harmonics and vibration in the two-stroke motors caused the composite to fatigue." Although a toughening agent added to the long-fiber thermoplastic improved its vibration damping, Stahl ultimately was dissatisfied with the prop's cosmetic appearance. A search for an alternative material led him to PlastiComp Inc. (Winona, MN, US).

PlastiComp's pellets (photo above) are made with continuous glass fiber strands, pulled through an impregnation die filled with molten polymer, says PlastiComp's VP of technology Eric Wollan. "It's a rod of aligned glass fiber and polymer, at fiber volume up to 60%, which we typically provide in pellets about 12 mm long." For Piranha, PlastiComp provides a proprietary formulation with reportedly 40% greater impact resistance than standard long fiber-reinforced materials, through the use of special additives that improve ductility and damp engine-induced vibration over

Better reverse thrust for big houseboats

Piranha has developed a new composite propeller that is well-suited to larger houseboat motors. It is designed to provide far greater reverse thrust than previous Piranha propeller designs, to facilitate easier maneuvering of the bigger boats. The proprietary blade-design changes to what is now known as Piranha's Hydrothrust propeller provide 400% greater reverse thrust than the company's standard propellers, with no loss of effectiveness in terms of forward thrust, and twice the reverse thrust of competing metal props.

Source | Conde Naste Traveler.com

a broad temperature range. It also contains carbon black for ultraviolet resistance and additives that impart a semi-gloss surface. "PlastiComp's Complēt MT long glass fiber nylon material easily provided the surface finish I wanted for our propellers," relates Stahl.

Although the initial propeller design was realized early on, Stahl continues to tweak product performance. One recent advance, Hydrobites, are small "flow fences" that control water flow and reduce turbulence vibration on the high-pressure side of the blades (noted in the drawing, p. 61) for better acceleration and maneuverability in tight turns. "Injection molding makes it easy to add feature details, like our Hydrobites, that would be difficult and expensive to produce in metal," Stahl points out.

Piranha's latest propeller iteration, intended for houseboats and service barges, improves reverse thrust, says Stahl. "It doesn't take much for inexperienced people to have difficulty because reverse thrust performance is significantly lower than forward thrust. Propellers are designed to push, not pull." Based on some proprietary blade design changes, Piranha's Hydrothrust propeller, he reports, provides 400% more reverse thrust than the company's standard propellers, with no change in forward thrust, and twice the reverse thrust of competing metal props.

A practical prop without the repair costs

Stahl reports that his company's injection molding process is very fast and problem-free. The modular nature of the design means that fewer molds are needed, which helps keep costs low. As an example, for the hub and hub extension parts to fit A-Series outboards, only two molds are needed because any blade, regardless of pitch, fits into the slots. He adds that all Piranha hubs are guaranteed for life, and of the tens of thousands sold each year, only a handful are returned for replacement.

As a result, Piranha's propellers are affordable and, with easily changed blades, have been an unqualified success, as evidenced by its extensive customer base. The ability to change a damaged blade instead of having to replace an entire prop reduces boat ownership cost. Given the low price point, in fact, customers often buy interchangeable blade sets of different pitch, enabling them to tune their boat's propulsion thrust to the intended use. Boating for speed? Transporting heavy loads? They've got the best of all worlds. CW

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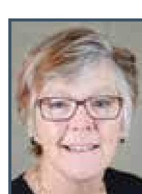
Read about composite props for large ocean-going vessels in "Composite propeller for Royal Navy minehunter" | short.compositesworld.com/minehunter

Watch a video that describes how to replace a broken propeller blade on a Piranha propeller | houseboatmagazine.com/2015/07/piranha-propellers-video

Watch a video demonstration of how a Piranha propeller fits together | youtube.com/watch?v=8gEVIvHn4Y8

Watch a pontoon boat equipped with a Piranha prop run at speed | youtube.com/watch?v=86kES8rwyLY



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