CW

CompositesWorld

Composites in Aeroengines: MARKET OUTLOOK

JANUARY 2015

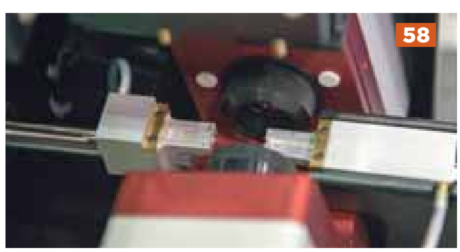
A Gardner Business Media Publication

№ 1 VOL 1

JANUARY 2015 / Vol: 1 №: 1

COLUMNS

» DEPARTMENTS



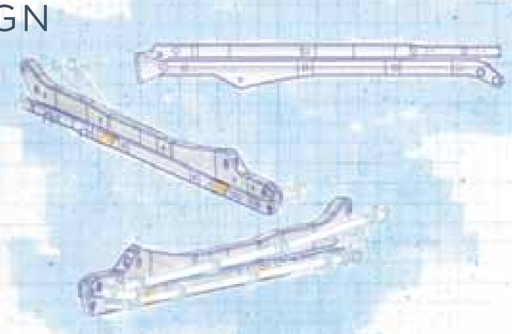
FEATURES

» ON THE COVER

Composite fan blades and inlet guide vanes, pictured here on a GE GEnx-2B turbofan jet engine designed for use on commercial transport aircraft, represent some of the most important — but today, definitely not the only — applications of advanced materials on these massive powerplants. See our examination of the market for composites in commercial jet engines on p. 32.

Source / Olivier Cleynen

FOCUS ON DESIGN



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POSTMASTER: Send address changes to *CompositesWorld* Magazine, 6915 Valley Ave., Cincinnati, OH 45244-3029. If undeliverable, send Form 3579. CANADA POST: Canada Returns to be sent to IMEX Global Solutions, PO Box 25542, London, ON N6C 6B2 Canada. Publications Mail Agreement #40612608.

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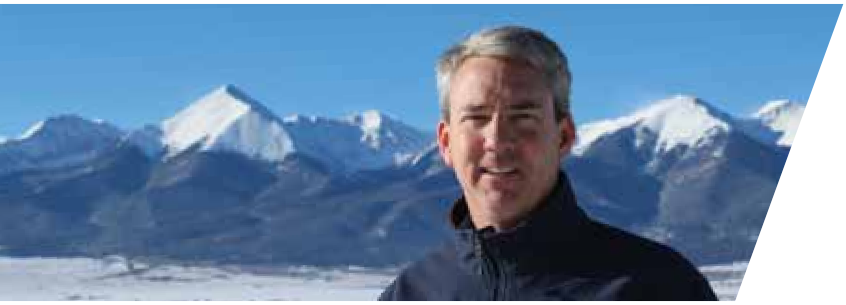


Happy 2015 and welcome to *CompositesWorld*.

» As I reported here late last year, we have made the decision to consolidate sister publications *High-Performance Composites (HPC)* and *Composites Technology (CT)* into one monthly publication, called *CompositesWorld (CW)*. You're holding in your hands Volume 1, Number 1 — sure to be a collector's item.

Although the name is new and we have updated the layout and design, you will find inside that much of the editorial content you have known as an *HPC* or *CT* subscriber lives on in *CW*. This includes regular features — Inside Manufacturing, Focus on Design and Work in Progress — and familiar columns.

However, there are two big differences in *CW*, and both are good. First, you will receive *CW* every month, instead of bi-monthly as was the case with *CT* and *HPC*. Second, you will find inside editorial content that spans the full breadth of the composites manufacturing universe, ranging, this month, from an assessment of composites use in aeroengines (p. 32) to a tour of ATK Aerospace Structures (p. 40) to the use of infusion in large marine structures (p. 48) to the application of carbon fiber in concrete pumping arms used in the construction industry (p. 62).

In *CW*, we will endeavor to bring you a diverse mix of stories that focus on the design, development and manufacture of composite structures sold into a wide variety of end-markets. You'll find stories from the aerospace, automotive, industrial, energy, building and construction, marine and consumer markets. You'll find articles about applications of carbon fiber, glass fiber, thermosets and thermoplastics in RTM, infusion, autoclave-cure, out-of-autoclave cure, filament winding, AFP, pultrusion and other manufacturing processes and process hybrids. You will find columnists offering their thoughts on the latest in testing, design, markets and opportunities.

Finally, if you were a regular reader of *HPC*, you will discover in *CW* that one of our best-read and most revered columnists is handing his pen to the next generation. Don Adams, who has written Testing Tech since 2005, is yielding to his son, Dan Adams, who debuts this month as the anchor author of CW Design & Testing. I think you will find Dan is as knowledgeable and capable as his father, and we look forward to many more years of Testing Tech advice, guidance and education. See Don's farewell message at right.

As always, no matter the name on the cover, we remain committed to serving your composites manufacturing information needs, whether it's in print, online or in person. We can do that only if we hear from you — when you think we've done well *and* when you feel we've stumbled. Give us a call, send us a note or track us down at a trade show and let us know how we're doing — and enjoy the new *CW*.

DON ADAMS: A FOND FAREWELL

"After 10 years of writing the Testing Tech column, I am ready to turn over to the next generation what became a great experience for me. I know that Dan Adams will do a commendable job, and hopefully will enjoy it as much as I have. It is satisfying to have a pulpit from which to introduce new concepts, correct errors in technical content, explore the 'rest of the story' or explain why sometimes things are the way they are, as illogical as they may seem. My editors at CompositesWorld, *Jeff Sloan and in particular Mike Musselman, have been a pleasure to work with. I know that Dan can look forward to the same great cooperation. In recent years, working closely with Dan Adams, I have learned that 30-plus years of experience in composite materials is perhaps even better than my 50-plus years, since he has at least 20 more years to share his extensive knowledge with you, our loyal readers. The very best to you all."*
— Don Adams

JEFF SLOAN — Editor-In-Chief

Hidden potential: An indifferent year for M&A belies a rich vein of opportunity for acquirers

» Despite a marked upswing elsewhere in the composites market, mergers and acquisitions (M&A) have declined following a 2012 peak. When the recovery was in full swing, investors were keener than ever to find "someone to buy." In fact, unprecedented levels of uninvested capital and record cash reserves (a result of scathing recessionary cost-cutting programs) contributed to a 15% hike in global M&A volume during the first quarter of 2014, compared to the same period in 2013 (Dealogic Revenue Analytics, 2014). Puzzling, then, to discover that despite above-average growth in the sector as a whole, composites bucked the M&A trend: Although 2012 saw the successful completion of more than 40 deals worth more than £2.3 billion (US$3.6 billion), as of October 2014, we were aware of only 15 finalized deals for the year to date.

Why the decline? Clearly, there is no shortage of ambition in the sector. Many firms are restating their commitment to growth by strengthening their competitive positions in key markets (e.g., aeronautics, automotive, construction and renewables) and extending their reach into new territories and technologies. There remains huge scope for consolidation in the highly fragmented value chain: Leading manufacturers are vertically integrating to gain greater control of supply chains, curtail costs and offer more comprehensive solutions to customers.

> ... the timing could not be better for either acquisition or divestiture.

So why does growth within the sector remain so resolutely organic? Experience tells us this decline in M&A activity lies principally in a *perceived* lack of viable acquisition targets. This sector is largely dominated by small and medium enterprises (SMEs), and there are more SEs than MEs. There is a surfeit of firms that are too small to register on investor/acquirer radar.

These companies — unproven, difficult to scale-up to mass production, with modest financials (a consequence, often, of focus on, and reinvestment in, their technologies at the expense of their bottomlines) — do not fit into the traditional M&A infrastructure. This is true, in part, because they also do not offer the *fee-earning potential* that most intermediaries demand. However, these firms can possess a wealth of unlocked potential and offer real strategic advantage to acquiring businesses. Smarter enterprises have been quick to take advantage. Indeed, anecdotal evidence suggests that smaller-scale acquisitions actually occur all the time, but largely go unnoticed by the press due to the modest amounts of money involved and the limited impact that such deals have on the industry as a whole. These acquisition targets are niche players whose few customers comprise, for the most part, larger manufacturers that monopolize the target's capacity.

Although such firms' technologies might not represent a step change in individual markets, the incremental improvements they offer deliver real competitive advantages to customers via streamlined operations, cost savings and efficiency gains. This is abundantly clear to their customers but invariably overlooked in the M&A context. Until, that is, there comes a tipping point at which a supplier's impact in the chain can't be ignored. Here, a customer will offer a buy out, frequently — because they underestimate their true value — for a fraction of their actual worth.

Smaller players in the composites space also are vulnerable to the nascent phenomenon of "acqui-hire" — acquisition based primarily on their engineering talent rather than their technology, products or services. This eliminates the need for the acquiring company to develop its own expertise. But because the majority of acqui-hires (85% or more) raise less than US$5 million in private equity (CBInsights, 2014), investors are invariably unmoved by such opportunities, favoring the US$20 million-plus deals that are more commonplace in other sectors.

The challenge of identifying these relatively low-value acquisition targets is exacerbated by composites sector fragmentation and by the attitudes of the companies' officers, who often have no interest in divestiture or investment. Often family-run, these firms have clear succession paths in place for the next generation, no desire to relinquish control and only a limited understanding of their real worth. A recent client, SLM Solutions GmbH (Lübeck, Germany), is a great example. A pioneer in selective laser melting, an innovative process suited to short series production of complex metal components, SLM had reached a critical developmental stage and required funding to take its operations to the next level. SLM was connected with a private equity firm that equipped it to fully exploit its technology. This contributed to a 10-fold increase in the company's valuation in just a couple of years.

Companies like this typically aren't looking at M&A and aren't likely to be geared for investment. But industry pundits forecast protracted growth and expect the sector's value to increase to US$10 billion or more by 2018, so the timing could not be better for those interested in either acquisition or divestiture.

And as *CW* went to press, indeed, we noted a significant increase in activity within the market. This included acquisitions by Hexcel (Formax), Saertex (Fiber Glass Industries), Toray (Saati) and North Technology (Future Fibres). CW

ABOUT THE AUTHOR

David Schofield is cofounder and managing director of Future Materials Group (Cambridge, UK), an independent strategic advisory firm. Its services include growth strategies, mergers and acquisitions, strategic partnerships and growth capital.

Composites in sporting goods: Been there, done that?

» I started playing tennis in 1972. I paid around US$10 for my first wood-framed racquet. I managed to get good enough to make my high school tennis team in Houston, TX. I played recreationally in college and for several years after that, and then dropped the sport when I moved to Detroit, MI, in 1984. Along the way I upgraded racquets, each time opting for the latest wooden versions — the aluminum racquets didn't feel right, and the early carbon fiber models that hit the market near the end of this period seemed too expensive and unproven.

Fast forward to 2008, when I decided to pick up the game again. Every racquet available was fashioned from carbon fiber, and there were multitudes of choices. I settled on a model from Wilson, which I have upgraded twice, since then, with the latest versions. I still own the last wooden racquet I purchased and have played with it for comparison. There *is* no comparison — my carbon fiber versions are so much better, offering a great balance of power and control. During the intervening 24 years, I also picked up golf and am now on my second set of clubs with carbon fiber shafts. (Like most carbon fiber sporting goods, the material was billed as "graphite"). I also became a snow skier and am on my fifth pair of composite skis. All of this makes me a repeat customer in multiple sectors of the composite sporting goods market. I made each iterative purchase because I believed the new models would improve my skill level and, for the most part, that has been true.

> ... has market saturation been reached in the once dynamic sporting goods sector?

But I'm beginning to think that, as a consumer, I am the exception rather than the rule when it comes to sporting goods rate of acquisition. After earning a reputation for several decades as the most dynamic market for composite materials, the sporting goods sector's growth rates of late have become rather anemic by comparison. Ten years ago, the quantity of carbon fiber used in sporting goods was equal to that used by all industrial applications combined and more than twice that used in the aerospace industry. In 2014, however, industrial applications are expected to consume four times the fiber used in the sporting goods industry, and the aerospace sector exceeded sporting goods consumption several years ago. Chris Red, principal of Composites Forecasts & Consulting (Mesa, AZ, US), forecasts growth rates of 11% and 12%, respectively, for industrial and aerospace applications out to 2020, with growth rates of only 4% for all consumer applications, which includes sporting goods and the faster-growing electronics segment. And I have seen one other forecast for sporting goods that predicted a *decline* in carbon fiber consumption between 2010 and 2020!

What can one read into this data? Has market saturation been reached in the sporting goods sector? Is the noted durability of composite materials partly responsible for the slower growth rate because fewer consumers have a need to replace broken equipment? Is what people already own "good enough" for the frequency and competition level at which they participate? One possible explanation is that improvements in performance today are, at best, incremental. I can recall in the 1990s, the introduction of a number of new high-modulus, high-strength carbon fibers that were immediately rolled out to market into high-priced and higher performance fly-fishing rods — to great fanfare. Golf shaft designers quickly took advantage of these new fibers to adjust nuances like torque and flex points. Driven by growing popularity of cycling races like the Tour de France, carbon fiber bicycles saw numerous innovations in the 1990s and 2000s, in materials and fabrication methods. These were times of rapid innovation. Today, however it seems like minor changes are promoted as major ones. In tennis, Wilson introduced a small amount of basalt fiber into some racquets a few years ago, and this year Head has introduced a racquet with a layer of graphene in the handle. Good for advertising? No doubt. Improved performance for the average player? That might be a bit more subjective.

Increasing regulations in sport also might be stifling innovation. In motorsports, Formula 1 teams were early and eager to adopt carbon fiber, then higher-modulus versions, at any cost. Other racing formats began to incorporate composites, but today, each motorsport class has restrictions in place to prevent "richer" teams from dominating. Competitive cycling and sailing also have various restrictions relative to equipment design. These limits also might be damping growth.

Who knows? Here's what *I* know: Wilson has just introduced a new line of tennis racquets, a couple of which incorporate braided layers of carbon and aramid in addition to unidirectional carbon. This very afternoon I will be trying them out, looking for the next edge on the courts. It's been 2 years since I last purchased a racquet — time for an upgrade. CW

ABOUT THE AUTHOR

Dale Brosius is the head of his own consulting company, which serves clients in the composites industry worldwide. Services include strategic planning, market analysis, assistance in mergers and acquisitions activities and technical support. His career has included positions at US-based firms, Dow Chemical Co. (Midland, MI), Fiberite (Tempe, AZ) and successor Cytec Industries Inc. (Woodland Park, NJ), and Bankstown Airport, NSW, Australia-based Quickstep Holdings. For three years he also served as the general chair of the Society of Plastics Engineers' annual Automotive Composites Conference and Exhibition. Brosius has a BS in chemical engineering from Texas A&M University and an MBA.

Tensile testing of composites: Simple in concept, difficult in practice

» Among the most common properties reported for fiber-reinforced polymers are those obtained from tensile testing of a unidirectional (UD) composite in the fiber direction. These properties include modulus of elasticity, Poisson's ratio, tensile strength, and ultimate tensile strain. The tensile test that measures these properties is, on the face of it, very simple: A thin strip of a UD composite is placed into the wedge grips of a mechanical testing machine and loaded slowly in tension. To determine the modulus of elasticity and Poisson's ratio, strains are measured during the initial stage of the test, using strain gages or extensometers. Loading continues to ultimate failure, the point at which tensile strength and ultimate tensile strain are determined. In practice, however, obtaining the desired results can be rather difficult.

Measuring the modulus of elasticity and Poisson's ratio is not the problem. These properties are measured at load levels well below the point of failure, typically corresponding to strain levels between 0.1% and 0.3%. The tensile strength and ultimate tensile strain values are the challenges, and they become more difficult to obtain as the specimen's tensile strength increases.

> ... tensile strength and ultimate tensile strain values are the challenges.

Why the difficulty? For starters, it requires a relatively large load to produce specimen failure, and it's no easy task to cause failure in the test section before failure occurs elsewhere. The specimen, therefore, must be designed in such a way that stress during the test will be greater in the central test section than in the load-introduction regions on each end. To do so, the cross-sectional area in the central section must be smaller than the area at each end. For metals and unreinforced plastics, the width of the specimen is gradually reduced leading into the central test section (Fig. 1). Although width tapering, or "dog-boning," appears to be an attractive option, in the case of UD composites, axial splitting of the specimen often occurs well before ultimate failure, effectively producing an *un*tapered specimen. These axial cracks result from the relatively low shear strength of the UD composite material coupled with relatively high shear stresses in these regions.

Although width tapering isn't an option, producing a specimen with greater thickness at each end is an attractive alternative. Rather than reduce the thickness of the composite specimen in the test section, the thickness at the ends is increased with bonded tabs (Fig. 2). Glass fabric/epoxy printed circuit board material is commonly used for tabbing for several reasons, including its commercial availably at low cost, its relatively low stiffness and its high strength. Further, the bonded tabbing strips also can be machined in the same manner as the tested composite material when individual specimens are cut from a test panel. Bonded tabs not only prevent axial cracking but also protect the surface of the composite specimen from direct contact with the serrated grip faces, which could cut or tear it during loading.

When a tabbed tensile specimen is tested, the load is introduced through shear at the gripped tab surfaces. The tabbing material and the adhesive bond must have shear strength adequate to transfer the load into the composite to produce failure. However, it's not enough to simply produce specimen failure. A "good" tensile test is one that measures the *fullest extent* of the composite material's tensile strength during the test. That requires a uniform distribution of axial stress throughout the composite test, or gage, section between the tabs. Toward that end, a tabbing configuration must be designed to minimize the stress concentrations produced in the tab termination region. Although there are several geometric and material parameters that can be used to design a tabbed tensile specimen that minimizes stress concentrations[1], the following four parameters are, perhaps, the most important.

TAB TAPER ANGLE: An effective means of minimizing the stress concentration is to taper the tab thickness, effectively "feathering" the load into the specimen gage section. Although it's tempting to use a very small tab taper angle to minimize stress concentrations, there are practical limits. Out-of-plane peel stresses produced at the tip of the tapered tab increase as the taper angle decreases, leading to failure of the adhesive bond. This design consideration is often overlooked, and it is not uncommon for the tips of the tabs to debond from the tensile specimen prior to ultimate failure — a highly undesirable outcome because it effectively eliminates the benefits of the tab taper. Tab debonding can be detected as audible "pings" and, sometimes, observed under low magnification during testing. The choice of a tab taper angle involves a compromise between minimizing stress concentrations and preventing tab disbonding. ASTM D 3039[2]

FIG. 1 Width-tapered tensile specimens with axial cracks.

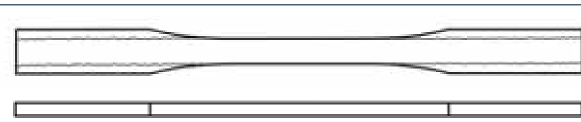
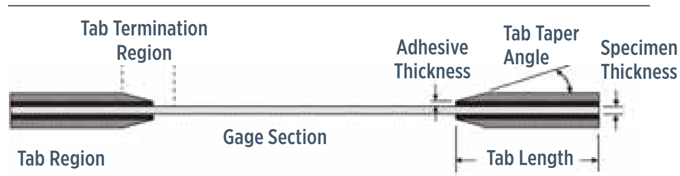


FIG. 2 Typical tabbed composite tensile specimen.



Source (both illustrations) / Dan Adams

suggests a tab taper angle of 7º-10º when testing 0º UD composites with wedge grips. However, the taper angle should be increased or the adhesive bond strength improved if debonding of the tab tips is detected.

TAB LENGTH: The minimum tab length depends on the load required for specimen failure and the shear strength of the adhesive. An increase in tab length reduces the stress concentration in the tab termination region, but reductions are minimal beyond a tab length of ~40 mm. The tab's entire untapered length should be gripped during the test to minimize peel stresses at the tab termination. Therefore, use the longest tab length permitted by the test grips, with a minimum untapered length of 40 mm.

ADHESIVE LAYER THICKNESS: A thicker adhesive bondline can reduce the stress concentration at the tab termination because the adhesive is more compliant than the tab and composite material. Epoxy adhesives that yield high strength in thicker bondlines are available. Although the reduction in stress concentration as bondline thickness increases is less pronounced when using tapered tabs, increasing the adhesive thickness to 1-2 mm yields a justifiable reduction.

COMPOSITE SPECIMEN THICKNESS: This parameter is often overlooked, but the load that must be introduced to produce a gage section failure decreases as the specimen thickness decreases. In fact, decreasing the thickness of the composite specimen, when possible, is the most effective means of mitigating the previously discussed problems with tabbed tensile specimens.

Although difficulties in obtaining accurate strength measurements from UD composite tensile testing often can be addressed through improved specimen design, careful fabrication of tabbed specimens is also important and cannot be overlooked. But the word of encouragement in all this is that the difficulties diminish with decreasing specimen strength. Therefore, those who can successfully perform tensile tests on 0º UD composites can likely do the same with any other fiber orientation or layup. CW

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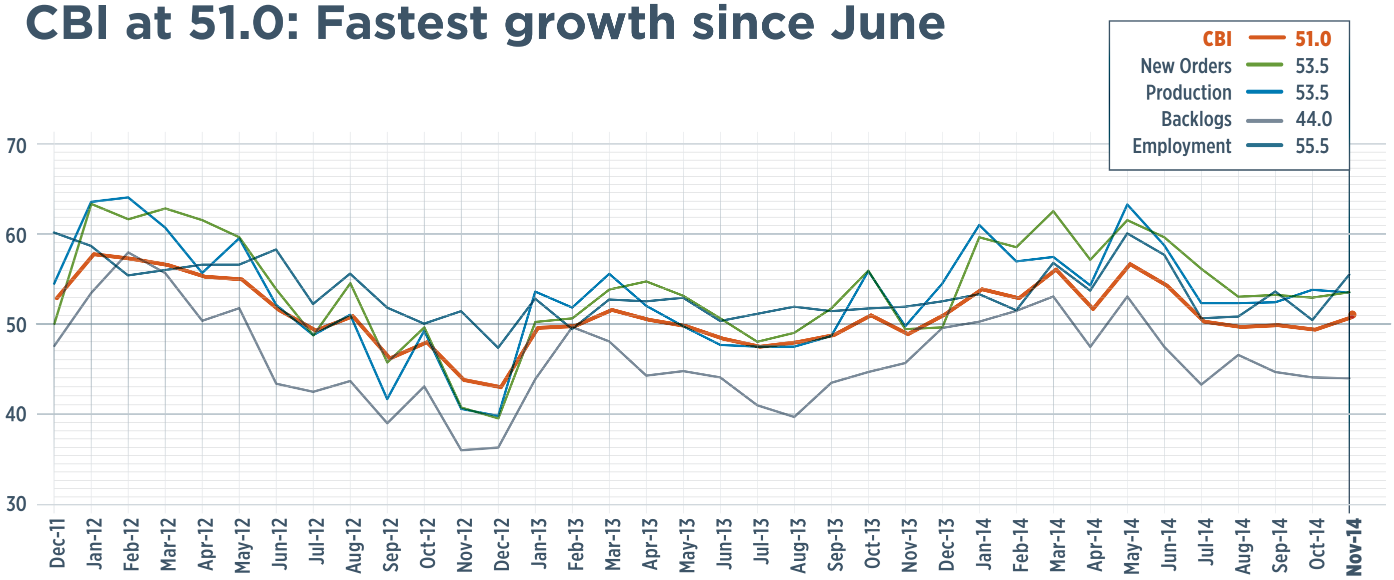
ABOUT THE AUTHOR

Dr. Daniel O. Adams is a professor of mechanical engineering and has been the director for 18 years of the Composite Mechanics Laboratory at the University of Utah and vice president of Wyoming Test Fixtures, Inc. (Salt Lake City, UT, US). He holds a BS in mechanical engineering and an MS and Ph.D in engineering mechanics. Adams has a combined 35 years of academic/industry experience in the composite materials field.

CBI at 51.0: Fastest growth since June



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

» With a reading of 51.0, the CompositesWorld Business Index for November 2014 was up from October's reading of 49.6, and showed that the composites industry in the United States had expanded for the second time in 3 months. The industry had been bouncing between moderate growth and contraction since July. Although the index had been relatively flat for five months, the month-over-month rate of change had grown in 4 of those 5 months. The annual rate of growth had decelerated for 3 months, but in November, the industry was still growing at a decent rate.

New orders in the US were up, again, for a 12th consecutive month at a rate of increase that had remained fairly constant for 5 months in a row. The production subindex showed expansion for the 11th month. Although its rate of expansion had slowed sharply in the May-August timeframe, it had remained virtually unchanged during the previous 4 months. Backlogs continued to contract at nearly their fastest rate since the fall of 2013. Compared to one year earlier, the backlog index had contracted for 2 months. Annually, the rate of growth in the backlog index fell below 10% for the first time since May 2014. As was true in October, the solid growth in its annual rate of change in November was a good indication that capacity utilization and capital equipment investment will increase into the second quarter of 2015. Employment continued to grow, increasing at its fastest rate since June, after rebounding in October from relatively weak growth in 3 of the previous 4 months. Exports continued to contract but at a rate noticeably slower than that seen in October, a significant drop attributable to the rising US dollar. US supplier deliveries continued to lengthen at a fairly steady rate after falling, in October, to its slowest rate since November 2013.

Through October, material prices in the US had increased at a rate that had been slowing since June 2014. In November, that index reached its lowest level since September 2013. Prices received were flat in November after falling, marginally, for the first time since March 2014. Future business expectations recorded a big jump after declining in October to a low point last recorded in September 2013. Expectations have been on wild up-and-down swings since June.

US composite manufacturing facilities with more than 50 employees continued to expand at a decent rate in November after posting an October growth rate nearly 10 points lower than in September — the prime reason the overall CBI moved from growth to contraction in October. Fabricators with 20-49 employees, however, contracted for the 3rd month in a row. Although facilities with 1-19 employees contracted for a 5th month, November was easily the slowest contraction.

Regionally in November, the US West was the best performer for a 4th consecutive month and was the only region to grow in all of the 4 preceding months. The Northeast and Southeast also grew in November. The North Central – East and North Central – West had contracted, for the most part, since July 2014.

Future capital spending plans in November were above US$1 million for the first time since June 2014. And, it was the first time the month-over-month rate of change had grown during that same period. Although the annual rate of change was still growing, it was growing at its slowest rate since the CBI began in December 2011. CW

ABOUT THE AUTHOR

Steve Kline is the director of market intelligence for Gardner Business Media Inc. (Cincinnati, OH, US), the publisher of *CompositesWorld* magazine. He began his career as a writing editor for another of the company's magazines before moving into his current role. Kline holds a BS in civil engineering from Vanderbilt University and an MBA from the University of Cincinnati.

New directions in the CompositesWorld include the advent of materials database organizations, gains in oil & gas exploration and early word from *CW's* Carbon Fiber 2014.

ARCHITECTURE

Hotel's event pavilion faithful to past with composite facelift

A composites-intensive exterior cladding project in the UK, now complete, has transformed the High Bullen Hotel's former tennis facility into its new Palazzo event pavilion, pictured here. Officially opened when the hotel hosted the Devon Tourism Awards 2014 on Nov. 19, the building's exquisite stonework is actually the product of a unique multi-material composite sandwich panel construction process developed by Acell Industries Ltd. (Dublin, Ireland).

To expand the scope of its services, the High Bullen golf and spa hotel, located on a former country estate in Devonshire in the southwest of England, wanted to convert its little-used tennis site into a flexible space for weddings and meetings. Local authorities, however, insisted on a renovation consistent with the shire's traditional architecture. Facing the enormous expense necessary to incorporate into the pavilion the authentic 19th-Century "Devon stone" masonry characteristic of the hotel's stately main building, the hotel's owner contacted Acell for help with a cost-effective alternative.

Acell's patented molding technology combines sheet molding compound (SMC) skins and a core of frangible yet fire-resistant mineral foam in a low-pressure compression molding press. Aluminum molds are custom-cast from fiberglass master models layed up directly on, and pulled from, natural materials. It is thus possible for Acell to replicate virtually any planar architectural design or surface in the mold surface, including not only classical finishes, such as stone, wood and brick, but very contemporary designs as well, says Michael Frieh, Acell's executive director. Color in the stone surface was duplicated by applying powdered iron oxide and sand grains to the textured composite panels. The result was a match for Devon stone.

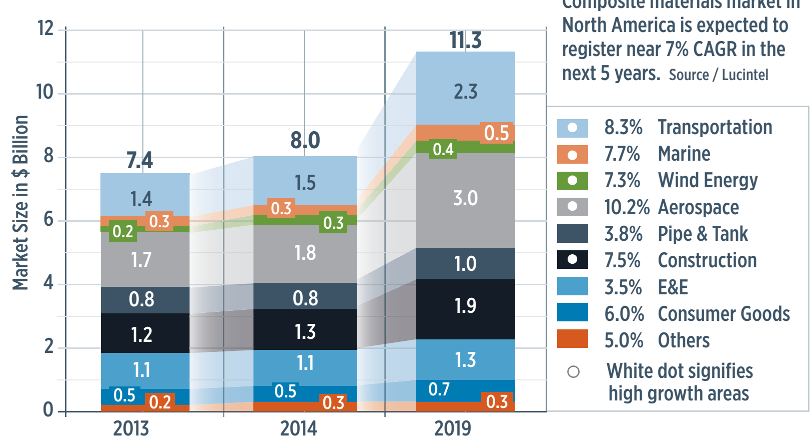
Acell also replicated the look of slate in the building's composite roof sheathing and fabricated the event space's interior walls and all of the decorative elements, including columns, statuary, and details of its domed ceilings. Walls were made with glass-reinforced gypsum (GRG, foam-cored gypsum board). Frieh says the rehabilitation project was completed in only six months. No surprise, then, that at the Palazzo's gala opening event, the High Bullen Hotel was presented with the Golden Award for "Large Hotel of the Year," sponsored by UK-based Hotel Perfect, a hotel management software company.

Learn More in *CW's* article on the cladding project's early stages online | **short.compositesworld.com/AcellClad**

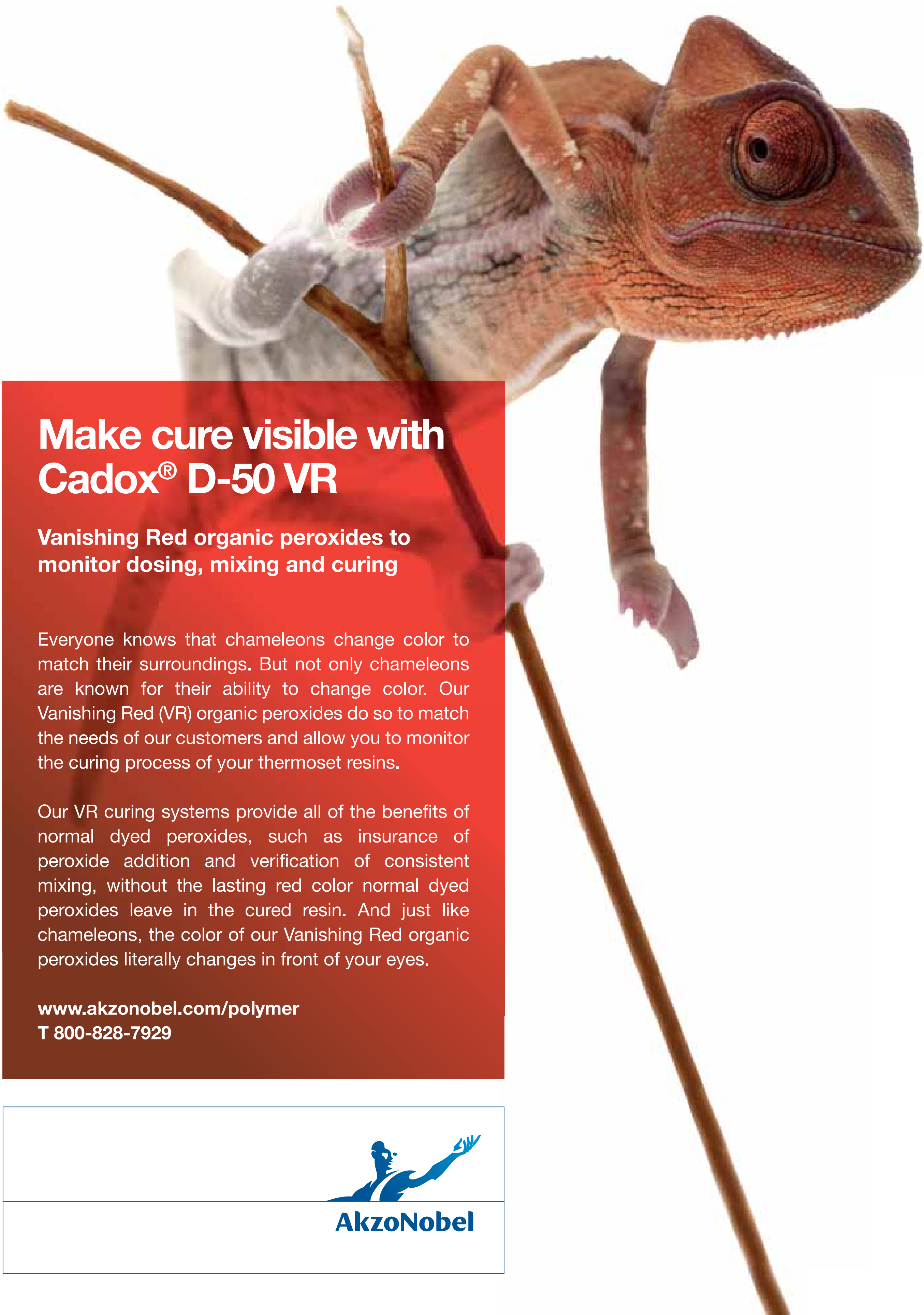
FORECAST

Composite Materials Market Forecast in North America

Dr. Sanjay Mazumdar of market research firm Lucintel (Irving, TX, US) presented a paper at the 2014 CAMX event, titled "Status of Composites Industry 2015: Market Potentials and Mega Trends." According to his presentation, the composites industry likely grew 5.8% in 2014, and is expected to reach a value of US$10.3 billion by 2019, representing a compound annual growth rate (CAGR) of 6.6%. Mazumdar foresees that strong transportation, aerospace and construction sectors will drive the growth rate, as shown on the chart at right.



Composite materials market in North America is expected to register near 7% CAGR in the next 5 years. Source / Lucintel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Growing materials library seeks composites industry submissions

If you're a designer for Adidas, Motorola or Toyota, where do you get information about cutting-edge material developments? A global consultancy, Material ConneXion (MCX, New York, NY, US), is one option. Its 70,000 members, worldwide, include corporate giants, such as IKEA, General Motors and Fisher Price, Nike, Samsung, Samsonite and Target as well as architects and industrial design firms.


Source / Material ConneXion

MCX's current library, available physically *and* online, contains more than 7,500 materials (see photos), 400 of which are composites-related. More than half of Material ConneXion's staff are material scientists, specialists in a particular material technology (polymers, ceramics, etc.) or sustainability experts. The company seeks to bridge the gap between science and design. MCX is seeking new submissions. No fee is required but submissions are reviewed by an independent jury, which adds 30-40 new materials to the library each month.

Learn more online | short.compositesworld.com/MatConneX


Face-To-Face, NPE2012

AUTOMOTIVE

Tools for collecting, managing and using autocomposites data

As the composites universe expands into new markets and applications, resins and fiber reinforcements of many types are, increasingly, landing on the desks of design engineers who have little or no experience with composites. Nowhere is this more common than in the automotive industry, whose denizens are drawn to composites' compelling strength-to-weight properties but repelled by its multi-material complexity. Complicating matters is a dearth of standardized, uniform, easily accessible composites material property data that might help designers

Source | Granta Design

and engineers navigate the unfamiliar composites materials landscape. Seeing this challenge, Granta Design (Cambridge, U.K.) is developing the Automotive Material Intelligence Consortium (AutoMatiC), which, it hopes, will help map the autocomposites design landscape by generating best practices for materials information and its use.

Established in June 2014, the Consortium comprises manufacturers and suppliers from the automotive and off-highway sectors. Members plan to optimize tools that will help organizations to manage all of the diverse materials-related data they need, to get it all in one place, to capture information about the relationships between linked items of data, and to apply this information resource to practical problems. They also intend to share lessons learned and, thus, improve practices. Each has committed to provide Granta with guidance, as it optimizes these tools for automotive applications.

Consortium members have the Granta system, called GRANTA MI, installed in-house and use it to manage corporate materials knowledge. A second available software application, GRANTA MI:Materials Gateway, works from within various CAD/CAM, CAE and PLM software systems to provide direct error-free access to materials data.

Learn More about the AutoMatiC Consortium online at the CW Blog | **short.compositesworld.com/GrantaBlog**

Making epoxy composites recyclable by design

Connora Technologies (Hayward, CA, US) and Adesso Advanced Materials (Wu Xi, Jiangsu Province, China) have garnered much attention for their hardeners which make epoxy resins recyclable, marketed as Recyclamine and Cleavamine, respectively. Announced in a May 2014 press release, the partnership and the companies' technologies stem from the same beginning.

Connora's founder/CTO Stefan Pastine applied the concept of "designed-in cleavage points" from photoresist chemistry to polyamine hardeners for epoxies in 2009. Rightly engineered, he says, epoxy cross-links can be unlinked, yielding thermoplastic molecules. Thus, the matrix and fiber reinforcement in a cured composite can both be reclaimed.

After working with Adesso in 2010, Pastine formed Connora in 2011, connecting with Rey and Desi Banatao, co-founders of Entropy Resins (Hayward, CA, US), whose desire to develop sustainable, performance composites led to formulation of Entropy's Super Sap bio-based resins. Entropy has since served as investor and incubator for Connora, and Rey Banatao has taken the role of CEO to establish manufacturing partnerships and expand Connora's pilot plant and R&D facilities in Hayward. Banatao says products already include infusible and compression moldable systems, a latent cure system for prepreg, filament winding or pultrusion, and is developing one for automotive HP-RTM. Connora announced in Dec. 2014 an investment from Samsung Ventures (Seoul, Korea) to advance commercialization of Recyclamine.

Learn more online | short.compositesworld.com/REpoxyBlog

FORECAST

Carbon Fiber 2014: Will supply meet demand?

CompositesWorld's Carbon Fiber 2014 conference (Dec. 9-11, 2014, in La Jolla, CA, US) had just kicked off as this issue went to press, but the *CW* staff captured the following highlights from day one of this annual event.

In a report on his experience as the raw material purchaser for the Boeing 787, John Byrne, VP aircraft materials and structures at Boeing Commercial Airplanes (Seattle, WA, US), noted that the composites industry's relative youth (compared to metals technologies) was a substantial handicap. The new materials and processes strained Boeing's engineering resources and their implementation involved capital cost expenditures that were not fully anticipated, especially as the build rate increased. Further, he said the extensive use of composites in the 787 does not guarantee similar use in future craft. In short, he said, "It's going to be a tougher sell in the future to go to an all-composite airplane."

Mike Canario, VP/GM Americas at Hexcel (Stamford, CT, US), discussed the economics of carbon fiber supply and the metrics that drive capacity expansion. He noted that the high cost of polyacrylonitrile (PAN) precursor combined with high capital equipment costs for new carbon fiber manufacturing lines put a great deal of pressure on carbon fiber suppliers to maximize asset use to meet their cash flow requirements. This means that capacity expansion to meet demand is done, perhaps, more carefully and deliberately than carbon fiber consumers might like. "Under-utilized assets are the scariest thing for carbon fiber makers," he said.

"I feel the industry has really moved forward now, and we're well-set for the future." That was how consultant Tony Roberts summed up his annual overview of carbon fiber supply and demand. With the caveat that his numbers are quite conservative, Roberts opined the following: Although excess capacity exists this year, demand in 2015 should be 65,000 MT (less than the 76,000 MT he predicted in 2012) for all fiber types. Looking forward, 2020 demand will be 120,000 MT and by 2025, he foresees 170,000 MT, representing a value of US$4.72 billion. Lower-than-expected demand from automakers is the principal reason his 2014 figure falls short of his earlier forecast. On the supply side, Roberts predicted that by 2025, Japanese-owned companies will produce more than 50% of global carbon fiber (85,000 MT). Fiber suppliers based in the US and those in Europe will each, as a group, produce a roughly identical 10% (12,000 MT). China and Taiwan together could account for 10% (about 15,000 MT), but Roberts added the caveat that China's role is far from certain in the next 5 years because limited precursor supply and quality are currently barriers for startups. Other Asia-Pacific suppliers will produce another 11%. Producers based elsewhere in the world will supply the remainder (about 5,000 MT).

CW MONTH IN REVIEW

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

Toray acquires Saati's European prepreg business
12/15/14: With the deal, Toray completes its carbon fiber value chain in Europe, adding prepregging to its PAN precursor, dry carbon fiber, and CFRP parts manufacturing holdings. **short.gardnerweb.com/ToraySaati**

Hexcel buys 50% stake in Formax UK
12/15/14: The move ensures scale-up of knitting technology for Hexcel's noncrimp fabrics and other fiber reinforcements for aerospace applications and growing industrial markets. **short.compositesworld.com/HexForm50**

Benteler SGL to supply composite leaf springs for new Volvo *XC90*
12/15/14: The crossover SUV's rear-axle spring will be RTM'd in Austria, using Henkel's Loctite MAX 2 polyurethane. **short.compositesworld.com/XC90leaf**

DowAksa acquires 50% stake in prepregger c-m-p GmbH
12/15/14: Turkey-based carbon fiber producer's investment in the Germany-based prepregger will help both companies expand their reach into automotive and industrial applications. **short.compositesworld.com/DowAksacmp**

Boeing completes milestone for Commercial Crew system
12/01/14: Boeing has completed the Certification Baseline Review for its CST-100 spacecraft under NASA's Commercial Crew Transportation Capability (CCtCap) contract. **short.compositesworld.com/CST-100crt**

FORMAX glass fiber multiaxials achieve DNV certification
11/29/14: With its carbon multiaxials already certified, a major portion of FORMAX products have now been accredited by this leading certification body. **short.compositesworld.com/FORMAXdnv**

Kaman Aerosystems wins composites contract for Bell Helicopter
11/29/14: Kaman's Composite Structures - Connecticut Division will manufacture monolithic and cored components for commercial rotorcraft models. **short.compositesworld.com/Kaman-Bell**

TenCate to supply composite armor for the Royal Danish Navy
11/29/14: Lightweight modular armor kits to be installed on *Iver Huitfeldt*-class frigates and *Absalon*-class support ships over the next few months. **short.compositesworld.com/RDNarmor**

San Diego Composites expands. Again.
11/24/14: Expanding for the fourth time in its 11-year history, the company moves into a new 6,500m^2 facility. **short.compositesworld.com/SDCexp4**

SPE Automotive Div. names winners of Innovation Awards Competition
11/18/14: The SPE Automotive Div. hosted its 44th annual Automotive Innovation Awards Gala on Nov. 12 and announced 2014's winners in several categories. **short.compositesworld.com/SPEGala14**

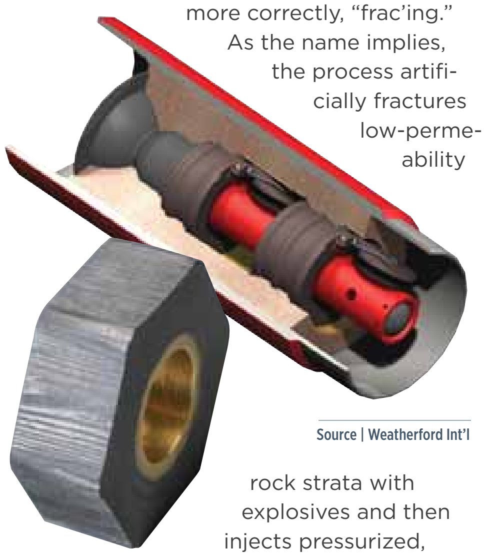
GKN Aerospace to lead wing technology research
11/17/14: GKN Aerospace to lead a 13-partner, 27-month effort to bring promising composite wing design, manufacture and assembly technologies close to market readiness. **short.compositesworld.com/GKNwingR**

Crawford Composites unveils Crawford *FL15* racecar
11/17/14: The Crawford *FL15* will be used, beginning in 2015, exclusively in the new announced Formula Lites racing series, sanctioned by SCCA Pro Racing. **short.compositesworld.com/FL15racer**

ENERGY

Frac'ing revolution demands more of downhole composites

An unprecedented US onshore energy boom during the past decade has brought the country to near fossil-fuel energy independence. Credit goes to a technology called hydraulic fracturing, often termed "fracking" or, more correctly, "frac'ing." As the name implies, the process artificially fractures low-permeability rock strata with explosives and then injects pressurized, sand-laced solutions into those fractures to facilitate oil and natural gas extraction.



Source | Weatherford Int'l

Source | Automated Dynamics

According to the Society of Petroleum Engineers (SPE, Richardson, TX, US), 60 percent of all new oil & gas wells globally are frac'ed, and 2.5 million frac'ing procedures have occurred since 2012 — more than 1 million of them in the US alone.

A single wellbore requires 10-40 multi-part, consumable tools called "frac plugs" (and accompanying "frac balls") to pressurize and perforate multiple oil- or gas-producing layers, called "stages."

Demand for these downhole parts exceeds 20,000 units per week, or more than 1 million units annually, according to one oilfield composites expert. Demand is high for these critical parts, which typically are made with composites because the composite is relatively easy to drill through at the end of the frac'ing operation, to make room for completion equipment.

Learn more about this booming oil & gas application online | short.compositesworld.com/CompFrac

ARCHITECTURE

USC architectural forum spotlights composites versatility for designers and students

In November 2014, *CW* attended "Performative Composites: Sailing Architecture," hosted by the University of Southern California's (USC, Los Angeles, CA, US) School of Architecture. Organized by USC School of Architecture professor Geoffrey von Oeyen, the event focused on the first exhibition of renowned architect Greg Lynn's project to design and build the *GF 42*, a 12.8m carbon fiber *foiling trimaran* (a three-hulled sailboat that "flies" above the water on thin foils that protrude downward from its rudder and keel). That project served as a vehicle for introducing architects and students who attended the event to composites and how they can actualize digital designs and enable exploration of new paradigms, such as tension-based structures and designs that integrate structure and surface.

The event included an exhibition that featured parts and design documents from the *GF 42* as well as design documents for the fiberglass-reinforced composite cladding fabricated by Kreysler & Associates (American Canyon, CA, US), which is currently being installed on a new expansion at the San Francisco Museum of Modern Art (SFMOMA, San Francisco, CA, US; short.compositesworld.com/ArchComp).

One forum issue was the lack of composites education at architectural design schools. According to industry estimates, composites comprise less than 0.5% of the ~3 billion MT of materials used in buildings annually, but Michael Lepech at Stanford University has shown that composites often outperform wood, masonry and steel, achieving a lower carbon footprint because legacy materials require more energy to manufacture, transport, assemble and maintain. Despite these facts, composites are rarely emphasized in studio classes required as part of design and architecture programs. To address that lack, California Polytechnic State University–San Luis Obispo, with funding from Kreysler & Associates and the American Composites Manufacturers Assn.'s (ACMA, Arlington, VA, US) Architectural Div., is enabling students to become familiar with composites and explore ways to integrate them into the structural support for the building envelope.


Source | CW / Photo | Ginger Gardiner

Learn More online | short.compositesworld. com/ArchEduc

MASS TRANSIT

Regenerative braking system for railcars relies on composite flywheel

A new flywheel-based regenerative braking system, the Digital Displacement hydraulic pump-motor transmission system from Artemis Intelligent Power (Loanhead, UK), has demonstrated that it can reduce the carbon footprint of trains. It stores and then reuses energy, by means of Ricardo's (Shoreham-by-Sea, West Sussex, UK) TorqStor high speed flywheels, which spin at 45,000 rpm. Artemia, Ricardo and rail technology firm Bombardier Transportation (Berlin, Germany) have formed the DDflyTrain consortium to demonstrate that this technology could work on diesel-driven commuter trains.

In an article at theengineer.co.uk by Julia Pierce, David Rollafson, VP global innovation at Ricardo, points out, "Every train journey involves a lot of stopping and starting, and so also a lot of braking and acceleration. If we can harvest some of the energy from braking and use this when the vehicle is gathering speed again, we can save a lot of diesel and, so, a lot of money for train operators." Pollution also would be reduced. "Pulling out of a station, diesel engines pump out a lot of pollution," he notes. "Adding stored energy to help acceleration would reduce this." The DDflyTrain system is reportedly easy to retrofit *and* it's modular — operators could scale up energy storage as finances permit. The consortium is now discussing application of its technology with a number of UK train operators.

Ricardo's TorqStor technology combines a modular, high efficiency, carbon fiber composite flywheel with a magnetic coupling and gearing system that enables a scalable range of energy storage capacities for different equipment applications.

Rollafson adds that the technology also could reduce costs and save fuel in commercial trucks and in mining and construction equipment: "We are actively seeking further opportunities to realize the benefits of TorqStor in new sectors."

Learn More online | short.compositesworld.com/PCSAforum

■ **Monolithic Master**

For its recent tests on non-production tooling manufactured from carbon fiber and benzoxazine resin via vacuum infusion, Leading Edge Aerospace (Wichita, KS, US) CNC-machined this female master mold from a block of monolithic graphite.

Source / Leading Edge Aerospace

Benzoxazines for OOA tooling

Can infusable formulations of this newer resin system produce aerospace-capable tools?

» Autoclave cure produces composite parts of the highest quality and lowest void content. All other things being equal, it's still the best insurance against part rejection. But today, all things *aren't* equal. The world in which part performance is everything and cost is no object is passing away, even in previously "cost-plus" defense and space-exploration sectors. Demand for faster production, particularly in the part-per-minute world of automotive composites, has exposed autoclave cure, with its lengthy temperature ramps, to the charge of "production bottleneck." Part consolidation and elimination of labor-intensive assembly steps — strategies made possible by the nature of composites and which justify their higher cost — have progressively increased the size of composite parts. Corresponding increases in autoclave volume have caused the autoclave's purchase price and operational costs to skyrocket out of reach for all but the biggest, most well-funded fabricators (see "Learn More" p. 27). Further, regardless of part size, the autoclave can make pre-production development cost-prohibitive and can discourage prototyping of tooling and parts, especially in prospective and/or one-off or few-of-a-kind programs.

... the world in which part performance is everything and cost is no object is passing away.

These realities have motivated the development of out-of-autoclave (OOA) epoxy prepreg (epoxy prepreg is the material form of choice for most autoclaved parts) and bismaleimide (BMI)-based alternatives that can be oven-cured. OOA epoxies and BMIs have seen significant development in tooling applications, but a relative newcomer, benzoxazine, continues to gain ground since structural composites-capable formulations were introduced in 2008 (see "Learn More").

Hot/wet performer

Benzoxazine boasts *continuous* hot/wet service temperatures, a key parameter in tooling applications, as high as or greater than epoxy's *maximum* hot/wet service temperature and also poses less risk of runaway exotherm that could contribute to tool distortion. Further, it can match BMI's performance in tools (e,g., <1% springback) and has the practical advantage of a significantly *longer* outlife — 6 months at room temperature (see "Learn More").

These factors were the motivation for recent tests on nonproduction tooling manufactured from carbon fiber and benzoxazine resin via vacuum infusion. Toolmaker Leading Edge Aerospace (LEA, Wichita, KS, US) partnered on the R&D project with an aerospace parts manufacturer to examine the viability of the infusion process as a substitute for prototype and production tooling typically made from prepreg cured in an autoclave.

LEA had previously produced tooling via vacuum infusion for other customers. A notable instance involved autoclave-capable infused tools for the wingskin, spars and other composite components that were incorporated into the *Scorpion*, a tactical fighter jet concept independently developed by Textron Airland LLC (Wichita, KS, US; see "Learn More"). The *Scorpion* tools combined a dry layup of 12K carbon fiber 2x2 twill fabric and an infusion-optimized epoxy resin, followed by a 12-hour cure under vacuum and a postcure. The use of benzoxazine for this new project enabled LEA and its partner to evaluate the performance of a tooling material that promised increased toughness and better high-temperature performance, compared with epoxy systems.

A female master model was CNC-machined from a 254-mm by 1,016-mm by 1,219-mm block of monolithic graphite. Next, approximately 12 plies of 2x2, 12K carbon fiber fabric were layed up on the master, bagged and vacuum infused with Beta Benzoxazine resin,

Infused Tooling Trial

Pulled from the graphite master, this vacuum-infused male tool comprises 12 layers of woven (2x2 twill) 12K carbon fiber fabric in a benzoxazine matrix. It was used to make about 15 test parts. Each part featured 30 plies of carbon/epoxy prepreg, and all were autoclave cured.

Source / Leading Edge Aerospace

supplied by US-based Airtech International (Huntington Beach, CA, US). The material has a T_g of 250°C, low water absorption and very low volumetric shrinkage on cure.

Rod Brown, composites manager at LEA, says the resin, as supplied in pails, is highly viscous, and required pre-heating to enable transfer into a feed tank equipped with a thermocouple-controlled temperature controller and lines for infusion and. There, the resin was stirred and gradually ramped up to the infusion temperature of 110°C. As the resin neared the infusion temperature, the tank was fitted with a lid and a vacuum was applied to de-gas the resin.

LEARN MORE

Read this article online:
short.compositesworld.com/BzOOAtool

Read more about oven-curable epoxy and BMI prepregs online in "Out-of-autoclave prepregs: Hype or revolution?":
short.compositesworld.com/OOAprepreg

The performance of epoxies, BMIs and benzoxazines in tooling is compared and contrasted online in "BMI and benzoxazine battle for future OOA aerocomposites":
short.compositesworld.com/BMIvsBenz

Read more about Textron Airland's independently developed *Scorpion* warplane online: "New *Scorpion* twin-jet to debut at Farnborough Air Show":
short.compositesworld.com/ScorpionFB

"Resin infusion produces autoclave-capable tools for *Scorpion* jet":
short.compositesworld.com/LEAjettool

In-oven infusion

When the resin was fully de-gassed, the tank was placed in the oven, in which the master had been pre-heated to the resin temperature. Resin feed lines were run from the tank to ports in the bagged layup. Operators then had a pot-life window of about an hour in which to infuse the layup. After infusion was complete, the oven temperature was ramped up to the cure temperature of 185°C and held for 4 hours. After cure, an egg crate-type backup structure was attached and the mold was removed from the master. Then the mold and backup structure, together, were postcured at 218°C for about 8 hours.

"The biggest challenge, working with this resin, is how to manage the material, lines and mold at the various temperatures," says Brown, noting that at 110°C, "you can still walk in the oven, briefly." That's *not* possible at the cure and postcure temperatures. "So everything has to be staged and ready to go," he cautions.

After postcure, the mold was CNC-machined with a 5-axis unit supplied by Anderson America Corp. (Pineville, NC, US) and then sanded, operations that were followed by application of filler and releases supplied by Chem-Trend (Howell, MI, US).

The finished tool, approximately 76.2 cm by 76.2 cm, was actually a reproduction of a corner section of a tool for a much larger production part. The benzoxazine-infused mold was used to make test parts, each comprising 30 plies of Cytec 934 carbon/epoxy prepreg supplied by Cytec Aerospace Materials (Woodland Park, NJ, US). The parts were autoclave-cured at 177°C and 6.21 bar.

"The tool performed great and maintained vacuum integrity through 15 test cycles," reports Brown. He adds that the decision to use benzoxazine rather than BMI to infuse the tool wasn't a strategic decision. "Both materials are very similar in terms of performance and cost," he notes. "We just tested benzoxazine because that's what Airtech offers. Our ultimate objective was to find some alternatives to prepreg and the autoclave."

Large aerocomposites?

That said, Brown sees the results of the project as promising. Although LEA and its aerospace partner have no plans, currently, to fund additional testing, he sees benzoxazine as an OOA tooling alternative for aircraft stiffeners, stringers and wing spars. "The real need for something like this is *large* tooling because that's where you enter into problems with an autoclave," he contends.

But he believes that eventual commercialization of OOA technology involving benzoxazine will hinge, in part, on how benefits and costs weigh out: The upside of using benzoxazine rather than epoxy to infuse tooling is that it produces finished tools that are more durable and can operate at higher temperatures. The downside is that it costs more and is trickier to infuse and cure at the necessarily higher temperatures required to ensure that it will have a viscosity low enough to fully wet out the reinforcement. Although the upside might have enough appeal among aerospace manufacturers to encourage its adoption, more trials and testing will be necessary to pave the path if it is to progress to commercial reality. CW

ABOUT THE AUTHOR

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Sub-8-minute cycle times for carbon/epoxy prepreg

Globe's Generation 2 RapidClave system passes another out-of-autoclave milestone.

» At the Society of Plastics Engineers' 2012 Automotive Composite Conference & Exhibition (SPE ACCE, Troy, MI, US), keynote presenters Calvin J. Bamford Jr., chairman/owner of Globe Machine Manufacturing Co. (Tacoma, WA, US) and Gary Lownsdale, then chief technology officer at Plasan Carbon Composites (Wixom, MI, US), described a jointly developed out-of-autoclave (OOA) process. The technology, they said, would reduce process cycle time for carbon fiber/epoxy prepreg laminates from almost 2 hours in an autoclave to a mere 17 minutes.

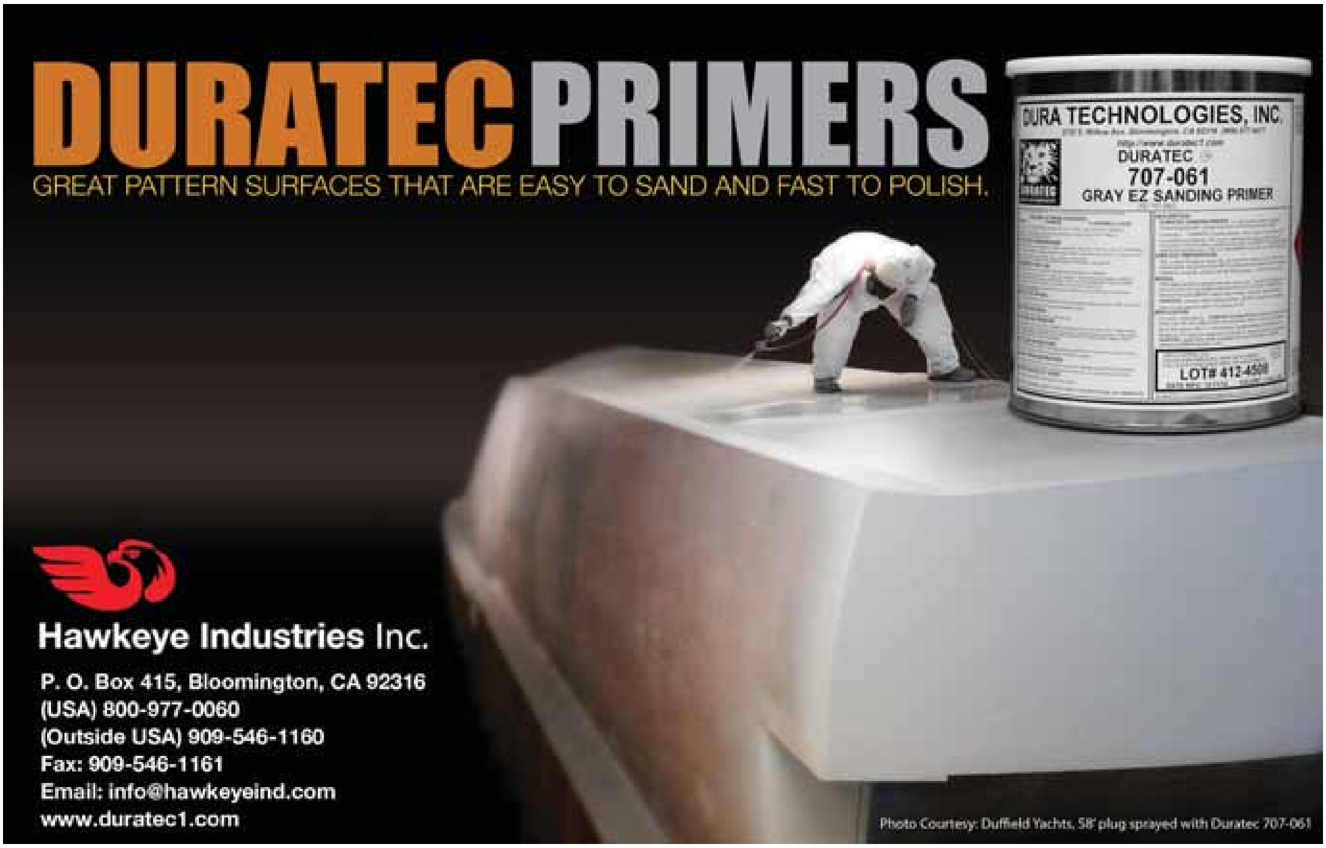
A few months later, the automotive world learned that Plasan would use that new technology, now dubbed RapidClave, to produce Class A bonded hood and roof panels for the new *Corvette Stingray* from General Motors Co. (GM, Detroit). Using a new process on a high-visibility nameplate like the *Corvette* was considered, by itself, innovative and risky. Equally big news, however, were the follow-up reports: GM's projected production volumes for the parts were an order of magnitude greater than those for any previous CFRP-bodied vehicle. Further, the demolded parts reportedly come out of their tools with such good surfaces that postmold finishing operations aren't as great a production bottleneck as they often can be. Therefore, part cost is justifiable for a sports car with a price tag of less than US$75,000.

8, 7, 6 Minutes ... the Countdown Continues

Globe Machine and Plasan scored a first in 2012, producing thermoset composite parts for Class A body panels on GM's *Corvette Stingray* with their unique RapidClave out-of-autoclave molding/curing technology in 17 minutes. This second-generation version of the RapidClave system clocked cycle times of less than half that duration in November 2014.

Source / Globe Machine Mfg. Co.

During that 2012 presentation, Bamford and Lownsdale also announced very ambitious plans to *halve* the cycle time on each subsequent generation of the RapidClave process. Although they were achieving 17-minute cycles, the speakers claimed that they had already modeled sub-10-minute cycles, using conventional resin and prepreg technology. That work paid off in November 2014, when Globe trialed its second-generation RapidClave system and successfully molded unidirectional carbon fiber/epoxy prepreg (6-8 plies, 0°/90° layup) at 8-, 7- and 6-minute cycles (button-to-button). Bamford reports part quality was excellent, and that parts were fully cured and showed less than 2% void content. Plaques produced during the trial were sent out for mechanical testing and, at *CW* press time, results were expected back by year-end 2014. »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Oil to water is the key

Lowsndale, who retired from Plasan in 2014 and now consults for Globe as president of TransTech International (Louden, TN, US), explains that a key difference between the first- and second-generation process technology is the medium for heat transfer. "In the first-generation presses, we used hot oil to heat our work pieces," he reports. "While that was fast, it wasn't fast enough. So, for generation two we're using a combination of water and hot-air impingement to simultaneously heat both sides of the part."

He notes this change yields faster heat transfer and tighter process control, which, in turn, expands the types of materials that can be processed. "Now we can work with the full range of epoxy resins — even snap-cure systems, which we couldn't use before because we didn't have fast-enough heat input or precise enough control over the heat cycle," he claims. Although trials, to date, have been run only with epoxy to get a meaningful comparison of cycle times and laminate performance between the RapidClave's first- and second-generations, Globe's "Gen-2" process reportedly isn't limited to epoxy.

> ... halving machine cycle time on each new RapidClave generation is still the primary goal.

Like the Gen 1 tooling, Gen 2 molds are single-sided. The part's B-side is closed off with either a bag or a bladder. Water lines are cut into the tool, which for this trial was produced by Globe in an unnamed metallic material. (Production parts on Gen 1 systems are formed with nickel-shell tools.) Although the Gen 2 system's superstructure looks no different from the outside and the basic process is said to be the same, the method is different enough that the company already has applied for a new series of patents. To ensure the widest possible application of Gen 2 technology, new RapidClave units reportedly are designed for use with either nitrogen or air, the former favored by the aerospace industry for its thick-section parts, the latter preferred by automotive molders, who fabricate thinner, bonded assemblies.

Based on positive results from the November trial, Bamford expected to run additional trials before year's end, using cored materials, something that hadn't been attempted with the Gen 1 RapidClave.

Asked, theoretically, what would be the biggest part that could be molded with a RapidClave system, Bamford laughed and said the development team has just finished that discussion. He believes it will be possible to produce a single part, such as a wingskin, up to 31m long and 5-6m wide in 30-40 minutes — a cycle time much shorter than the 8 hours he says is currently considered *fast* in the aerospace industry.

Lowsndale claims that, even on that scale, the basic process technology would remain the same. Further, the pressure mechanism would require only a thin column of air, so a large part wouldn't require as much machine volume to mold parts as one might assume.

RTM, ATL on horizon?

Work on RapidClave technology continues apace. Reportedly, Globe has been evaluating how thermoplastic matrices can be used in the system. "We've completed intensive engineering studies to prove the process will work for carbon-reinforced thermoplastics," Lowsndale reveals. Although he's tight-lipped about which resin chemistries they're using, he does say that they are working with several of the "best big resin suppliers" and that processes that variously employ thermoplastic tapes and press-side impregnation of carbon fibers are under investigation. Bamford emphasizes that halving machine cycle time on each new RapidClave generation is still the primary goal and the use of thermoplastics will be critical to that continuing effort. "We believe we need to do this to be competitive for higher production volumes and to compete with alternative processes, like RTM," he notes. But he also hints that the company has been working in parallel with RapidClave's Gen-2 development on what might become an "RTM-like" process, although there is no word yet on whether it will be a new machine or will be some kind of press-side work cell to create a preform/prepreg in thermoset chemistry that then can be moved into the RapidClave for forming. Bamford adds that Globe plans to introduce a series of "novel" work cells within the next 6-9 months that will complement the RapidClave system. These will include, among other things, methods for automated tape layup (ATL) for thermoset and thermoplastic matrices. Notably, the company already has applied for intellectual property protection for these new technologies.

LEARN MORE

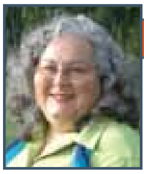
Read this article online:
short.compositesworld.com/RapidClav3

Read more about the genesis of the RapidClave process online in "Plasan sheds light on its automotive composites work in Michigan" | short.compositesworld.com/RapidClav1

Read more about the initial use of the RapidClave process to produce parts for the *Corvette Stingray* in "Faster cycle, better surface: Out of the autoclave" | short.compositesworld.com/V4Ty5Iv4

Expanding to meet the need

Both men acknowledge that breakthroughs are needed and desired by industry and that the demand is there for faster processing technologies. Because the Gen-2 system is now commercially available, Bamford says he expects to do more hiring and that Globe also will consider putting additional machinery production plants where they are needed to serve industry. CW



ABOUT THE AUTHOR

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Fully exposed in this shot, the nacelle components surrounding the General Electric GEnx turbofan engine provide a wide range of opportunities for advanced composites.

Source | Olivier Cleynen

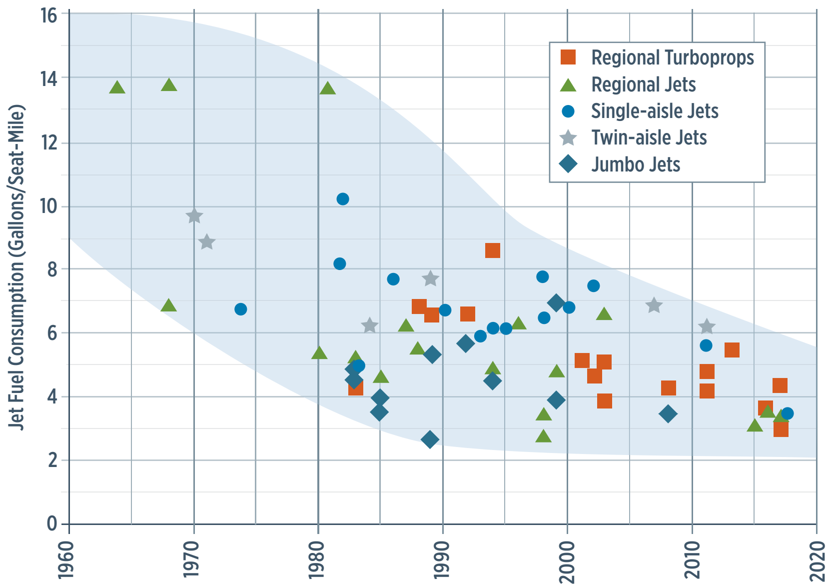
Composites in Commercial Aircraft Engines, 2014-2023

The drive to boost aircraft operating efficiency continues to fuel adoption of polymer matrix composites in jet engines.

» Aircraft are creatures of economics. Commercial transport planes whisk passengers and cargo around the world in hours, but only if they generate direct profit for the airlines that fly them. Business jets profit commercial enterprises, albeit more indirectly, by doing the same for growth-conscious corporate executives. Not subject to profit/loss evaluations, military aircraft nonetheless transport troops and equipment and provide fast, far-reaching armed defensive capabilities on the strength of profits hard won by those who pay taxes, tariffs and duties to the governments that field them. Although they vary dramatically in capacity and capability, these flying machines have in common that operating them poses an increasing — and potentially unsustainable — expense to their owners.

FIG. 1: The Evolution of Airliner Fuel Efficiency

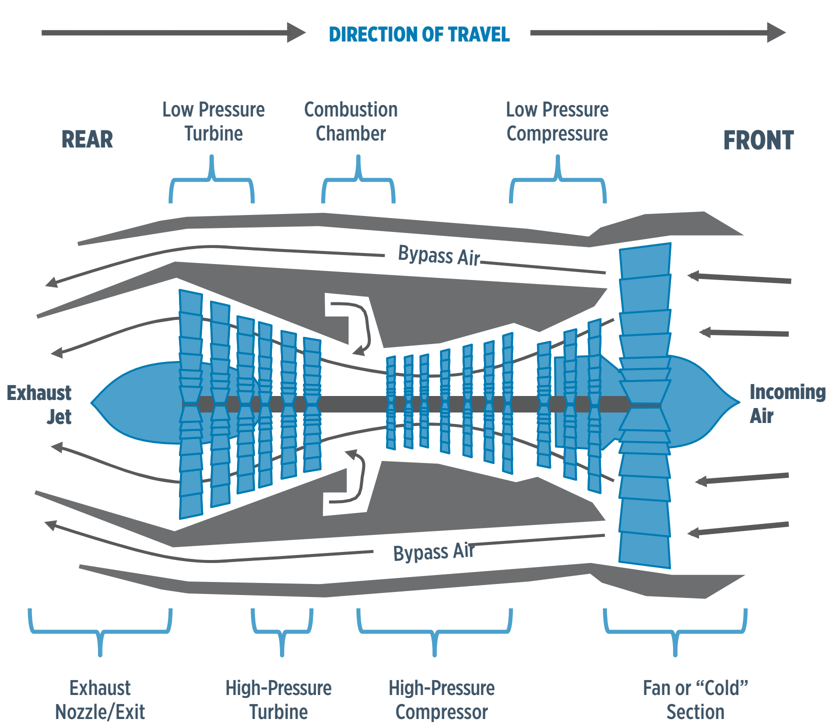
Decades of aircraft industry research have reduced the cost of owning and operating aircraft. These cumulative efforts have resulted in significant reductions in jet-fuel consumption.



Source | Composites Forecasts & Consulting

FIG. 2: Schematic of Typical Turbofan Engine Configuration

A turbofan generates thrust from incoming air that is directed into its core turbines, mixed with fuel and ignited, and air that is routed *around* the turbines. The larger the ratio of this bypass air to combustion air, the greater the engine fuel efficiency. Source | Composites Forecasts & Consulting



Today, no single aspect of aircraft operating cost looms as large as — or is more easily addressed than — fuel consumption. Since 1990, the cost of jet fuel has risen at an average annual rate of 7.7%. As a result, it's become the dominant cost center, particularly for commercial air carriers. At the turn of the millennium, says the International Air Transport Assn. (IATA, Montreal, QC, Canada), fuel accounted for 13-15% of direct operating cost. By 2006, it had soared to nearly 30%. At present, fuel represents 33-40% of global airline expenses and, even at somewhat moderated cost inflation, could soon climb to 50% or more.

In response to the concerns of commercial carriers, aircraft OEMs have devoted decades of research to reducing the cost of aircraft operation and ownership. These efforts have resulted cumulatively in some significant improvements. Since 1980, the average fuel burn per aircraft seat-km has been reduced by the following percentages:

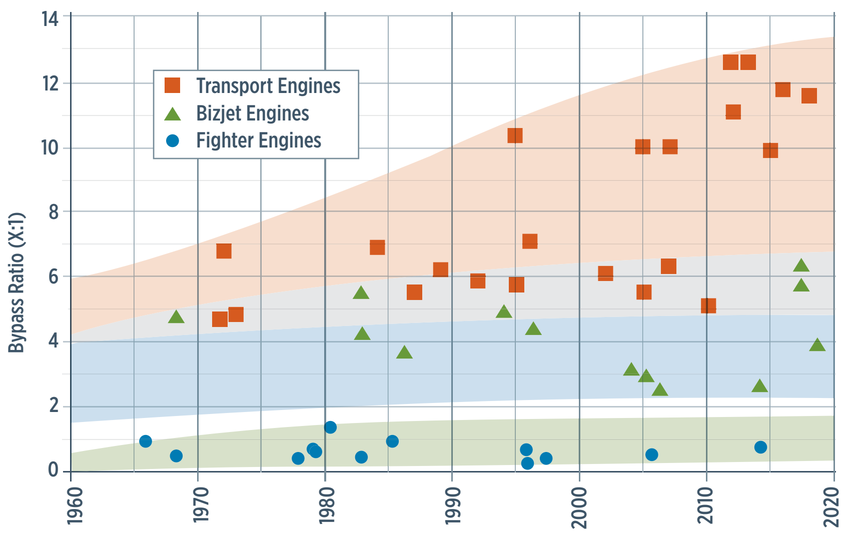
- Regional turboprops . 22%
- Regional jets 35%
- Single-aisle jets 35%
- Twin-aisle jets 27%
- Jumbo jets 9%

Continuing advances in aircraft and engine design are expected to make the newest versions of some of the most successful aircraft designs — commercial single-aisle transports (110-210 passengers) — nearly 50% more efficient than comparable aircraft introduced in the 1980s (see Fig. 1). Examples include the upcoming Airbus A320*neo*, the Boeing 737 MAX and the Bombardier *CSeries*.

On the strength of additional savings strategies, IATA reports that between 1990 and 2012, its airline members have been able to improve their overall efficiency by 46% — significantly more than the per-aircraft efficiencies noted above. Some of the additional gains come from enhanced operational practices. The replacement of older aircraft in airline fleets with newer models with improved aerodynamics and more efficient engines has been the greatest aid to airline efforts to avoid billions of dollars in fleet fuel costs. This is one reason that commercial transport OEMs have been able to continue to increase production and sales over the »

FIG. 3: The Evolution of Turbofan Engine Bypass Ratio

Generally, turbofan bypass ratios have steadily increased, especially in the engine families that support large transport aircraft. Source | Composites Forecasts & Consulting



past several years, despite trying economic conditions.

Efficiency drives design

The jet engines market spans a wide range of products that generate from 2700 N-m to 163,000 N-m of thrust. Generally speaking, those covered in this outlook are in the sub-classification of *turbofans*. Although there are many variations, turbofan engines feature a large fan section mounted on the front of a core turbine, with an additional turbine in the rear, all connected by a driveshaft (see Fig. 2, p. 33).

The turbofan generates thrust from two sources, the fan segment and the core turbine. Some of the incoming air captured at the engine inlet is fed into the core turbine's low- and high-pressure compressor stages and on into the combustion chamber where the compressed air and fuel are mixed and ignited. As the resulting high-temperature gas expands, it turns the rear-mounted high- and low-pressure turbines that drive the front fan and compressor and then provides propulsive force as it exits the exhaust jet. The majority of a turbofan's thrust, however, is the result of incoming air that is diverted around the compressor and turbine. The difference in the volume of air that bypasses the compressor vs. the air delivered to it is expressed as the "bypass ratio." Bypass thrust does not require direct fuel burn. In the quest to improve operating costs, therefore, engine manufacturers have steadily increased bypass ratios, particularly in the engine families that support large transport aircraft (see Fig. 3, p. 34). In general, the greater the bypass ratio, the better the fuel efficiency, especially at subsonic speeds.

■ LEFT: The composite fan blades and inlet guide vanes, as shown here on a GE GEnx-2B engine, represent some of the most important applications of advanced materials on turbofan engines.

Source | Olivier Cleynen

Larger bypass ratios, however, result in larger fan sections and, in turn, heavier turbofans. The GE Aviation (Cincinnati, OH, US) CF6 engine family, for example, entered service in 1973 with a bypass ratio of 5:1. The CF6's fan section accounts for 20% of total engine weight (~4,090 kg). GE's new GEnx turbofan, which produces about the same amount of thrust, has a bypass ratio of 10:1. Its fan accounts for 30% of the engine's 5,807-kg weight. Each kilogram added to the fan section necessitates 2.25 kg of extra support structure in the engine and the aircraft wing.

Design drives composites

To mitigate weight increases, aeroengine manufacturers have replaced metal with composites (see Fig. 4). Throughout the 1980s and 1990s, the application of composites in aircraft engines was relatively limited. More than half of the total composite volume was directly associated with nacelle components, such as thrust reversers, acoustic liners, cascades, blocker doors, radial drive fairings and cowlings. On some models, aramid fibers (often in the form of dry-fiber belts) were used to reinforce aluminum fan cases. Composite nose cones, a variety of air ducts and engine air-oil seals were fairly common as well (see Fig. 5).

When it entered service in 1995, GE's GE90 engine applied many more advanced materials and resin transfer molding (RTM) processing to introduce a number of new composite components — most notably, large fan blades made from hundreds of plies of intermediate-modulus carbon fiber prepreg. Since then, composite blades, fan containment cases, bypass ducts, stator vanes and a host of less glamorous detail components and brackets have become common not only in commercial jets but also in business and military aircraft.

FIG. 4: Turbofan Engine Composite Usage vs. Engine Dry Weight

Composites will continue to account for an increasing share of total turbofan dry weight with a commensurate reduction in that total. Source | Composites Forecasts & Consulting

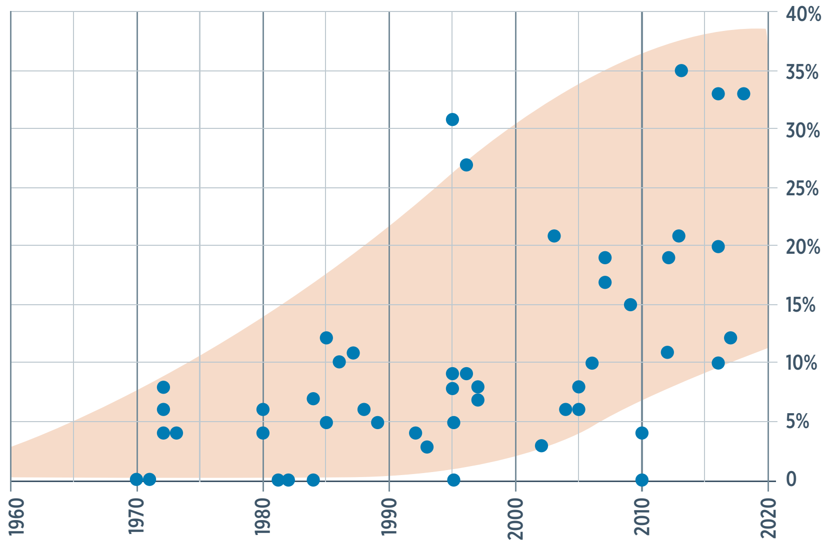


FIG. 5: Common Aeroengine Applications

Composites are making incursions into an ever-larger number of turbofan components.

Source | Composites Forecasts & Consulting

Turbofan Engine Section	Typical Applications
Fan Section	Spinner cones, fan blades, fan spacers, fan platforms, fan containment cases, bypass ducts, stator vanes, outlet guide vanes, various mounting brackets, cable trays
Low-pressure Compressor	Air-oil seals
High-pressure Compressor	Turbine shrouds
Combustor	(none found)
High-pressure Turbine	Fan exit cases
Low-pressure Turbine	(none found)
Exhaust/Exit	Exhaust nozzles
Nacelle	Inlet lips, fan cowls, access doors, acoustic liners, pylon fairings, blocker doors, thrust reversers and cowlings, support barrels

Composites flyaway outlook

Based on figures compiled by Composites Forecasts and Consulting (Mesa, AZ, US) in support of a recent production forecast for jets, turboprops and piston-powered planes during 2014-2023, we estimate that 67,710 turbofan-type jet engines will be needed to support expected global aircraft production (see Fig. 6). »

FIG. 6 Global New Aeroengine Production by Aircraft Type

The year-by-year expectations for aircraft jet engine production during the 2014-2023 forecast period (figures in engine unit volumes).

Aircraft Type	2005	2013	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2014 -23 Total
Commercial Transport	1,553	2,750	2,980	3,218	3,036	3,197	3,194	3,244	3,293	3,200	3,104	3,148	**31,613**
Regional Transport	530	332	326	354	384	380	426	398	412	372	312	308	**3,672**
Military Fixed Wing	435	530	574	584	664	680	691	682	716	698	682	682	**6,653**
Business Jet	1,885	1,646	1,924	2,365	2,618	2,724	2,745	2,715	2,566	2,514	2,518	2,550	**25,239**
UAS	1	33	27	35	37	23	27	45	56	74	103	106	**533**
Total	4,404	5,291	5,831	6,556	6,739	7,004	7,083	7,084	7,043	6,858	6,719	6,794	**67,710**

Nearly 47% of these engines will be destined for long-haul commercial transports. Business jets will consume the next largest number, accounting for about 37% of the market. Regional (short-haul) jets will make up about 5% of these deliveries. Military jets, including fighters and jet-powered unmanned aircraft, will require 11% — about 7,200 turbofans (plus some on-ground spares). Annual engine production has grown steadily since 2005 — engine deliveries totaled more than 5,800 units during 2014 — and is expected to peak in the 2018-2019 timeframe.

Engines and surrounding nacelles were expected to consume more than 16,320 MT of finished components, including those made of metals, composites and other materials, during 2013 alone. Of that total, composites accounted for an estimated 1,542 MT of flyaway weight — a significant increase over the roughly 454 MT delivered in 2005. Demand for composite aeroengine components will amount to nearly 1,680 MT in 2014, and we conservatively project growth to more than 2,765 MT per year by 2023 — based on known applications. Composites now represent about 9.5% of total engine flyaway weight. As the market matures during the years to come, this figure is expected to reach about 15%. And in the next 10 years, our study indicates that 23,587 MT of polymer composite structures will be manufactured in support of aircraft engine programs. This amounts to a US$16.2 billion market.

... we expect that North American manufacturers will control 70% of the engine market by 2023.

Nearly 85% of this engine-bound tonnage is destined for long-haul commercial aircraft. Regional jet programs are expected to account for about 3%. Business jets will consume another 8%, and military jets will need 4%.

Notably, nearly half of the projected total is earmarked for use on CFM International's (Melun, France) CFM 56 and LEAP 1 families, which are used extensively to power the A320 and B737, and will soon be aboard the emerging MS-21 and C919 single-aisle transports. CFM International is a joint venture of GE (Evendale, OH, US) and SNECMA (Courcouronnes, France, a division of SAFRAN), so it should not be surprising that GE is the next largest consumer of composite engine components. Combined, CFM and GE will represent about 72 percent of total aeroengine composites demand. Over the next several years, however, Rolls-Royce's (London, UK) Trent and Pratt & Whitney's (East Hartford, CT, US) PurePower engine families are expected to account for a considerable portion of the 28% balance.

The majority of the aircraft engines reviewed for this study are produced by European and North American manufacturers. Our research indicates the latter currently control the lion's share of total production, accounting for ~60% of the tonnage produced during 2014. France, through the SAFRAN group, holds close to a 30% share; Japan, Ireland, Italy, Spain, Belgium and Austria divide the majority of the remaining 10%.

Many engine manufacturers have significant in-house composites manufacturing capacity. GE Aircraft Engines, for example, has US facilities in Batesville, MS, Newark, DE, Baltimore, MD, Asheville, NC, and Ellisville, MS, as well as joint-venture subsidiaries. Rolls-Royce has reportedly purchased a large number of small fiber-placement machines for production of composite fan blades for upcoming engine platforms. Prominent tier suppliers in the engine composites segment include the following (with market shares noted):

- Albany Engineered Composites (Rochester, NH, US) . 12.8%
- C-Fan (San Marcos, TX, US) 8.7%
- Nexcelle (Cincinnati, OH, US) 8.8%
- GKN Aerospace (Worcestershire, UK) 6.0%
- Aircelle (Gonfreville-l'Orcher, France) 3.9%
- FACC AG (Ried, Austria). 3.6%

Based on existing applications and current work shares, US manufacturers are poised to significantly increase their market shares during the forecast period. Anticipating that the US dollar will remain weak vs. major European and Asian currencies, we expect that North American manufacturers will control 70% of the market by 2023.

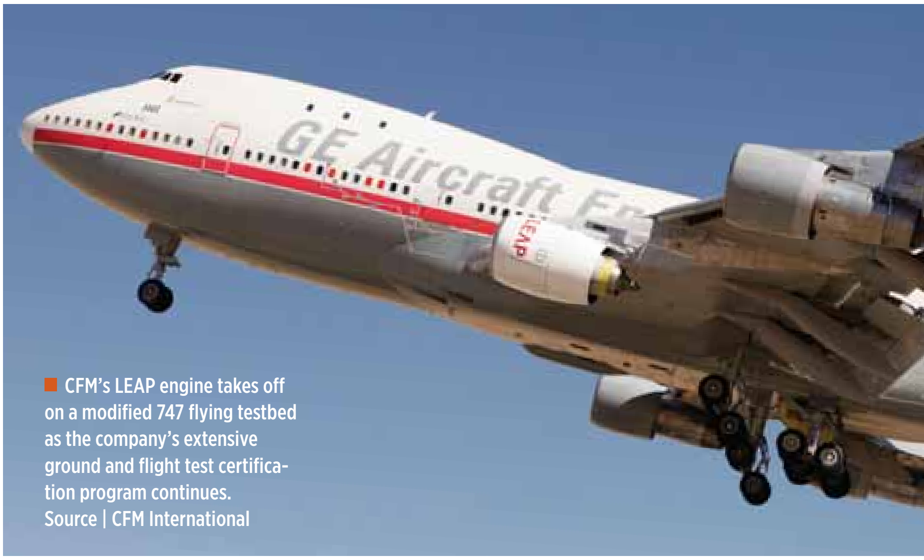
Processes and materials

Historically dominant, hand layup and autoclave cure of prepreg remains the most-used method for producing composite engine components. Filament winding also has a long history, but a much smaller role in aeroengines, as the method used to fabricate aramid fiber containment belts that surround fan cases.

Like fabricators of other aircraft structures, engine builders have long sought to drive down manufacturing costs and maximize production output and efficiency. That quest has led the former to develop automated tape laying (ATL), automated fiber placement (AFP) and infusion processes for large primary structures. But the latter have been drawn to methods more readily applicable to relatively small but more complex engine parts. A case in point is CFM's LEAP 1 (see photo at right), expected to enter service later this decade. Individually placed, autoclave-cured prepreg plies have been replaced in its fan blades by 3D braided preforms processed by RTM. This strategy reduces composite part complexity and yields a dramatically shorter cure cycle, cutting the cost per unit of weight saved.

Fig. 8 illustrates that autoclave/prepreg and RTM processes (the latter accounting for nearly 30% of production) will continue to dominate the market over the forecast. Although RTM has proven to be the most adaptable processing alternative, multiaxial compression molding is emerging as a viable means to mold some smaller components, including fan platforms and, perhaps more interestingly, thrust reversers — an application historically dominated by suppliers based in Japan.

In terms of fiber reinforcements, our study found that glass, carbon and aramid fibers will continue to be incorporated into engine component laminates. Aramid, as noted, will reinforce fan containment cases. Glass fibers, currently, are used primarily in »



CFM's LEAP engine takes off on a modified 747 flying testbed as the company's extensive ground and flight test certification program continues.
Source | CFM International

FIG. 7 Advanced Aeroengine Composites Demand by OEM

Data for projected turbofan engine production by individual OEMs indicate that CFM International (Melun, France) and one of its parent companies, GE (Evendale, OH, US), together, will own a 72% market share.

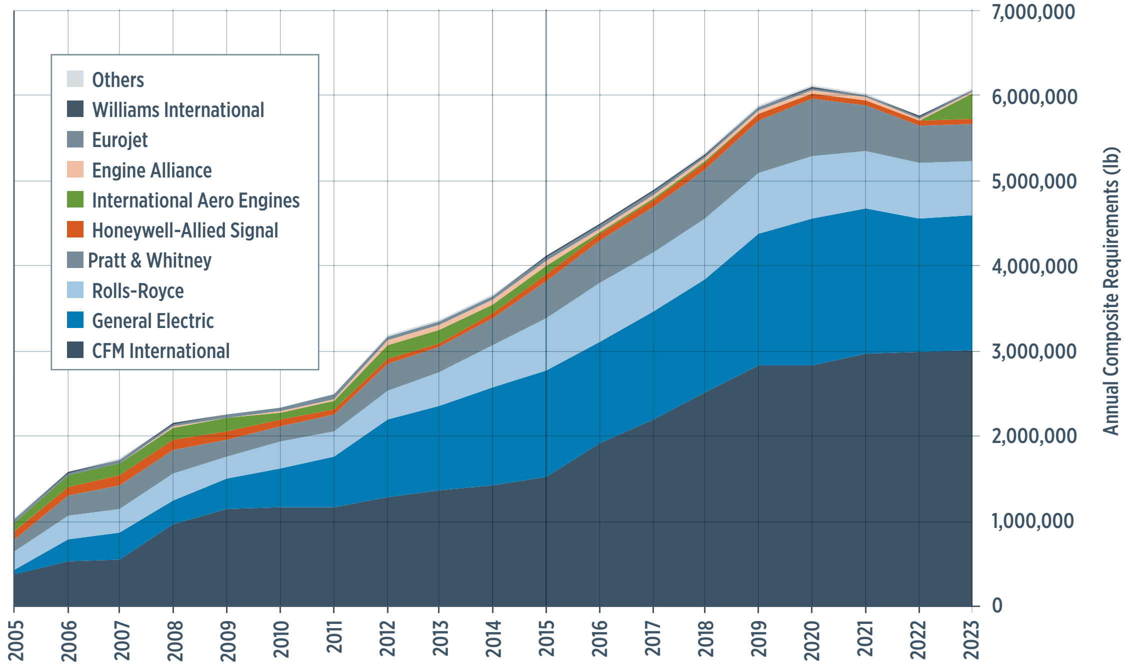
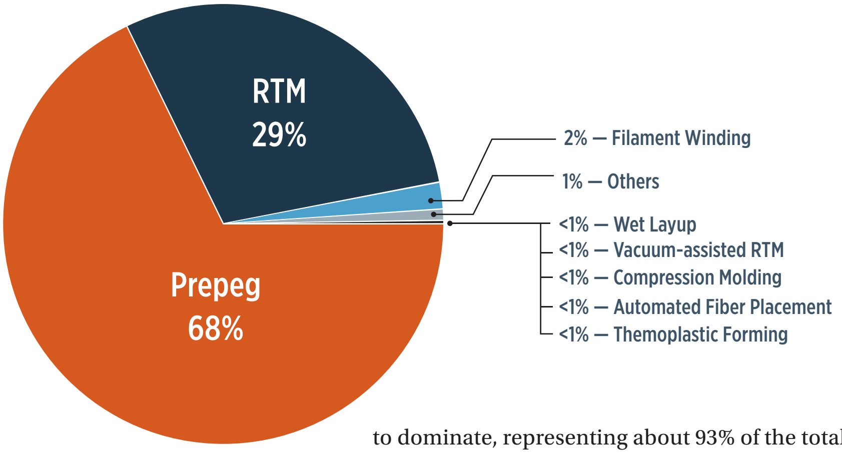


FIG. 8 Aeroengine Composites by Manufacturing Process

Although autoclaved prepreg still dominates in the hierarchy of processes used to build composite parts for jet engines, the use of resin transfer molding (RTM) has increased significantly, and compression molding is likely to gain a larger share.

Source | Composites Forecasts & Consulting



acoustic panels incorporated into nacelles. Standard-modulus carbon fibers will continue to reinforce some nacelle elements, but high-strength, standard-modulus and intermediate-modulus carbon fibers, together, will account for about 94% of the 12,474 MT of raw fiber destined for this market in the coming 10 years. High-performance, intermediate-modulus fibers alone will meet an estimated 83%, or 10,400 MT, of the forecasted fiber demand.

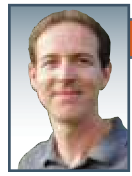
This study also looked at matrix resins. We estimate that 7,530 MT of resin materials will be required to support the prepreg, liquid RTM resins and molding compounds used to produce engine structures during the coming decade. Standard and toughened epoxies (121°C-cure and 176°C-cure) are expected to dominate, representing about 93% of the total, followed by bismaleimide and polyimide. Given the high-temperature applications in engines, this study also tracked the use of cyanate esters, phenolics, benzoxazines, phthalonitriles and thermoplastics, but only thermoplastics appeared in any sizable quantity, largely for engine brackets and for emerging thrust-reverser applications.

Future flight plan

As a result of continuing cost pressures on aircraft operators, the market for composite aeroengine components has nearly tripled since 2005. The durability and superior mechanical performance of carbon fiber composites, in particular, has been instrumental in enabling the production of high-bypass turbofans, through larger fan blades and lighter supporting and surrounding components in larger fan sections. Based on growing aircraft production rates, especially for commercial aircraft, our previously noted (and conservative) 2014 estimate of nearly 1,680 MT of composite engine components, worth more than US$1.1 billion, will grow, by 2023, to more than 2,665 MT of structures, valued at US$1.7 billion. Cumulatively, over the 2014-2023 forecast period, about 23,586 MT of engine composites will be fabricated.

That will provide considerable growth impetus for manufacturers of composite engine parts and their respective supply chains. Material suppliers will need to expand their raw materials output. After accounting for trim and waste in manufacturing processes, our study found that manufacturers will require nearly 33,113 MT of fiber and resin systems — primarily intermediate-modulus carbon fiber and toughened-epoxy resin systems. At base raw material prices, this represents more than US$1.4 billion in sales. After conversion into prepregs, infusible preforms, molding compounds and other intermediate product forms, the sales value will easily exceed US$2 billion.

On a final note, however, we should point out that the service-temperature range of polymer matrix composites effectively limits them to the engine's front "cold" section. Although some polymer matrices can safely operate at temperatures greater than 177°C, the majority of engine weight is still concentrated in the engine's "hot zone," where low- and high-pressure turbine segments can see operating temperatures in excess of 1,315°C — well beyond the capabilities of even the most exotic polymers. The high cost and manufacturing difficulty associated with high-temperature metal alloys for these applications present a large target for future weight reduction efforts based on ceramics and ceramic-matrix composites. Now under development for use in CFM's LEAP 1, in the turbine rotor shroud, these materials are likely to find application elsewhere in the next several years, including, for example, exhaust nozzles and bearings. Although the extent to which these newer materials might be applied across the broad spectrum of aircraft engine components has yet to be determined, there is considerable ground for engine-builder experimentation. In fact, potential opportunities for replacement of metals with ceramic matrix composites could be larger than those already claimed by polymer matrix composites. CW



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ATK Aerospace Structures: Clearfield, Utah

High-volume, high-precision fiber and tape placement for the aerospace industry are among many specialties for this composites manufacturing behemoth.

ATK Aerospace Structures literally grew up with the composites industry. In the 1950s, the company was established to filament wind rocket motor cases for the U.S. defense and space programs. Today, it's difficult to find an aerocomposites program in which the company does not or did not have its hand: Current commercial aircraft programs include the Boeing 787 and Airbus A350 XWB as well as the General Electric GEnx 2B and Rolls-Royce Trent XWB jet engines. Military aircraft include the Airbus A400M and Boeing's C-17 *Globemaster* transports, Lockheed Martin's F-22 *Raptor* and F-35 *Lightning II* fighter aircraft and AgustaWestland's 609 helicopter. Space systems have included the *Delta IV* and *Atlas V* launch vehicles and the International Space Station (ISS).

ATK Clearfield

ATK works out of this and several other buildings like it in a large industrial park near Clearfield, UT, US. The unassumingly ordinary appearance of the buildings' exteriors, however, contrasts sharply with the complex and sophisticated composites engineering performed inside.

Source | ATK

Spread out over three US states, ATK Aerospace Structures now maintains manufacturing facilities in Dayton, OH; Iuka, MS; and Clearfield, UT. The Clearfield installation is in an industrial park about an hour north of Salt Lake City. It occupies the site of what was, during World War II, an inland US Navy installation deemed beyond the reach of Japanese aircraft that might accost the US from the Pacific

Ocean off the California coast. There, a collection of long, but undistinguished buildings that are now home to ATK betray little from the outside about the substantial activity inside. The Clearfield facility houses three primary activities: Aircraft Commercial (57,000m^2, 17% cleanroom), Military Structures (60,000m^2, 12% cleanroom) and Case Manufacturing (18,000m^2). Clearfield employs 800 people, and the Aerospace Structures division as a whole employs 1,000 people in total.

When CW was offered the opportunity to tour Clearfield operations, the firm's largest facility, the door was open to document how the company built on its filament-winding legacy to become one of the aerocomposites sector's leading innovators and one of the most aggressive, disciplined and experienced high-performance composites fabricators in the world.

CW's guide through the Clearfield facility was Barrett Milenski, R&D engineer and 9-year employee of ATK. Although Clearfield still produces rocket motor cases and mints a long list of other structures — engine cases, nacelles, fuselage components, door springs, pivot shafts, wingskins, wing cover stringers, fixed skins and pressure vessels — the tour's first stop put the spotlight on two recently developed product types that dominate production in terms of numbers and illustrate ATK's enduring commitment to pushing the limits of technology.

Stringers and frames

Clearfield manufactures fuselage stringers and frames for the Airbus A350-900 and A350-1000 and the center and aft fuselage frames for the Boeing 787-9 and 787-10. Milenski pointed out that manufacture of these complex parts is among the most challenging enterprises ATK has faced. The stringers and frames for the A350-900 alone involve 698 different part numbers, and a single shipset constitutes 900 components. Since A350-900 production began, ATK has delivered more than 30,000 stringers and frames for the aircraft. Although automated tape placement technologies have matured significantly in recent years, matching such volumes with off-the-shelf technology was not possible. The company employs, instead, two in-house-developed technologies that combine unique fiber preparation with a high-volume process that enables ATK to hit the A350's production targets and give ATK, »

Table 1 Stringer and Frame Manufacturing

ATK's Automated Stiffener Forming (ASF) process enables the company to meet several stringer and frame attributes, including a variety of length, yaw, pitch and radius values.

Stringer Attribute	Capability
Length (x-direction)	18,000 mm
Yaw (y-direction from centerline)	150 mm
Pitch (z-direction)	1,000 mm
Frame Attribute	**Capability**
Curvilinear length	>8,000 mm
Radial envelope (min.-max.)	2,300-3,000 mm
Web height (max.)	150 mm
Attribute: Stringer & Frame	**Capability**
Minimum ply length	300 mm
Ply positioning tolerance	± 2.5 mm
Fiber orientation	°3.0°
Material Preparation Machine (MPM) fiber gap/lap	1.25 mm max./0 mm

Table 2 Automated Fiber Placement Machines

ATK developed the world's first automated fiber placement (AFP) machine in 1982. Today, the company operates 15 AFP units, seven of which are in Clearfield. Four of the seven were built in-house. Two were built by Fives Cincinnati (Cincinnati, OH, US), one was built by Electroimpact (Mukilteo, WA, US).

Name	FPM 1	FPM 2	FPM 3	FPM 4	FPM 5	FPM 7	ACCE 1
Vertical/Horizontal	H	H	H	H	H	H	V
Vendor	ATK	ATK	ATK	ATK	FIVES	FIVES	EI
Axes	6	7	7	7	7	7	7
Mandrel weight (x 1,000 lb)	29	60	20	60	60	60	N/A
Mandrel diameter (ft)	11	16.3	8.7	16.3	16.3	16.3	N/A
Single-/multi-workstations	Single	Multi	Single	Multi	Multi	Multi	Multi
Tow capacity	12	32	24	32	32	32	16

Table 3 ATK Structural Spar Demonstrator

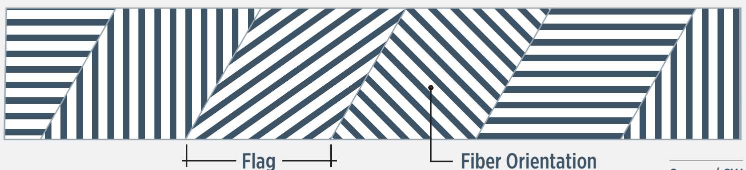
The ASF-made demonstrator spar was 3,000 mm long and tapered from 571 mm wide at the base to 444 mm wide at the tip. It has three sections, with a different flange angle, flange/web radius, laminate thickness and fiber orientation in each.

Dimensions	Section 1	Section 2	Section 3
Length (mm)	1000	210	1790
Web width (mm)	571-533	533-514	514-444
Flange height (mm)	102	102	102
Flange angle	2°-4°	4°	4°-5°
Flange/web radius (mm)	27	27/10	10/8
Laminate thickness (mm)	16.8	16.8-5.6	5.6-4
Laminate orientation	0°/90°/+45°/-45°	+45°/-45°	+45°/-45°

Automating Material Preparation and Stiffener Formation

ATK's Material Preparation Machine (MPM) passes prepreg through a proprietary cutting system that yields *flags* (job-specified lengths) of prepreg at 90°, 0°, +45° and -45° (see drawing), and then re-spools the re-oriented material. ATK's Automated Stiffener Forming Machines (see drawing) then upspool that MPM'd material and passes a male mold under a series of fixed-location compaction heads, which conform the material to the mold surface.

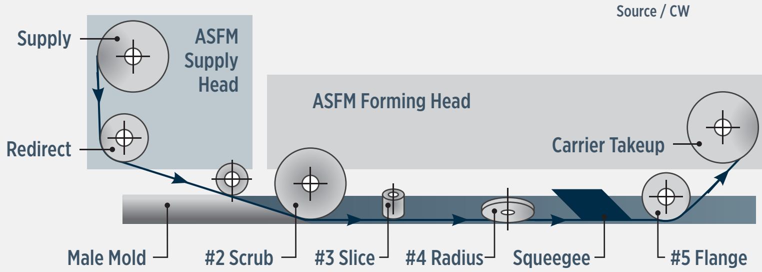
MPM 1



Source / CW

MPM 2

Source / CW



Source / ATK

in this arena, a real competitive advantage. The first is the aptly named Material Preparation Machine (MPM), a continuous process that does just that. The machine accepts up to 600m long rolls of 600-mm wide unidirectional (UD) HexPly carbon fiber prepreg tape supplied by Hexcel (Stamford, CT, US), unrolls it, and passes the prepreg through a proprietary cutting system. The cutter yields *flags* — the term for job-specified lengths — of prepreg at biases of 90°, 0°, +45° and -45°. The system then re-orients each flag to a pre-programmed angle, puts it back in line with other flags, and re-spools the re-oriented material (see drawing at left). The material is then slit and re-spooled to one of several widths used at the plant. The new prepreg roll comprises a series of UD flags oriented at a variety of angles that meet specific load requirements of particular stringers and frames (see Table 1, p. 41).

After it leaves the MPM, each roll is delivered to a cleanroom in the Clearfield plant called the Aircraft Commercial Center of Excellence (ACCE), where it is loaded onto one of five Automated Stiffener Forming Machines (ASFM) — ASFM-L0401, ASFM-L0402, ASFM-L0501, ASFM-R0201 and ASFM-R0202. Machines designated with an "-L" are used to manufacture linear parts such as stringers. Machines designated with a "-R" are radial machines that manufacture frames. With this second in-house technology, ATK has fully automated stringer and frame manufacture. The principle of ASFM operation is relatively simple yet the machine is fast: A male mold, for a C-, Z-, or I-beam or hat cross-section, is passed under a series of fixed-location compaction heads, which push the MPM'd material onto the tool surface, conforming it to the wide variety of shapes, angles and dimensions presented by stringer molds. ASFM-L0401 and ASFM-L0402 each have four heads to provide scrub, side, radius and flange compaction operations (see illustration, on this page).

ASFM Yield

ATK's in-house-developed Automated Stiffener Forming Machines (bottom photo) quickly, efficiently and precisely turn out racks of highly differentiated fuselage stringers for the Airbus A350-900 and A350-1000 (top photo) and fuselage frames for both the Airbus A350 and Boeing 787. One shipset of stringers and frames for the A350-900 includes 698 part numbers — 900 parts in total. ATK makes all of the stringers and 60% of the frames for the A350-900.

Source | CW / Photos | Jeff Sloan

Transport-friendly Floor

After stringers are placed by an ASFM, the layed-up tools are bagged and then transferred on racks over this roller-ball floor system to an autoclave for cure. The flooring allows molds to be easily moved and manipulated by ATK personnel, avoiding the cost and time involved in using cranes.

Source | CW / Photo | Jeff Sloan

NDI Assessment

Fuselage frames at ATK are molded on a proprietary machine, but the pre-production layup of the molds used in the frame-making process involves this 16-tow Electroimpact fiber placement system, which builds prepreg frame "rainbows" on a cutting table, cuts the rainbows to shape, and then places them on the mold in the frame forming system. Finished frames and stringers are then assessed via nondestructive inspection (NDI) by this ATK-designed and -built phased-array system (inset).

Source | CW / Photos | Jeff Sloan

"ASFM-L calls it pitch, roll and yaw," says Milenski, referring to the myriad of tool types that must be accommodated by an ASFM. "Each tool has its own swoop, twist or curve, and the ASFM has to be able to put down material for each one." The ASFMs not only lay down prepreg with precision, but can build a laminate up to 66 plies thick, and can do so 10 times faster than is possible with manual processes. Further, says Milenski, ASFM processing requires no intermediate debulks. On average, stringers up to 18m in length can be laminated, formed, bagged and ready for cure in approximately 2 hours.

Although stringers present daunting variation, Milenski says the *most* complex aspect of the ASFM process is mold manufacture and management. Each of the 698 stringers and frames on the A350-900 requires a unique Invar mold. Each tool, Milenski notes, has a carbon fiber caul, and most of the molds are of the Omega-shape type. Each mold is affixed with a radio frequency identification (RFID) tag that identifies the tool's location in the plant. In the future, the RFID tags will be integrated into the lamination process to identify the part and signal to the ASFM where and how prepreg should be applied.

"These molds are incredibly important to us and our customers," Milenski points out. Hundreds of tools are stored horizontally on tall racks just outside the ASFM fabrication room. Locating a stringer on the »

ATL Skins for the F-35 Fighter

This Fives VIPER automated tape laying (ATL) system is one of two used by ATK to lay up BMI laminate skins for the F-35 *Lightning II* fighter jet. Each ATL is fed by a spool bank (bottom photo) that "rides" with the placement head on the machine's control platform (background in image). The multifunctional mandrel rotates after tape placement so that the layup can be laser inspected for gaps, FOD and dimensions. Source | CW / Photos | Jeff Sloan

rack, moving it, loading it in the ASFM and then returning to its rack is, in itself, a full time job in Clearfield. "Managing and maintaining them properly is a big part of what we do."

After each ply layup, a mold is robotically pushed out from under the ASFM compaction heads. Off the end of the layup bed is a Virtek Vision International (Waterloo, ON, Canada) laser projection system that is used to verify proper ply placement and check for foreign object damage (FOD). Layups that pass this test are bagged and prepared for autoclave cure. Once bagged, the parts pass through a cut in the cleanroom wall to the cure staging area.

Up to this point, mold manipulation has been accomplished primarily with forklifts and robots, but getting a mold into the autoclave is a manual process, yet one ATK has simplified with a bit of creative thinking. A bagged mold is loaded onto a tool transfer cart, about 500 mm wide and 900 mm tall. A metallic mold on such a cart might normally be moved by crane, tug or forklift, but at ATK it's done over a large floor — spanning the space from the ASFM clean-room to the autoclaves — embedded at regular intervals with small roller balls (see top photo, p. 43). The transfer carts, pushed by one or two ATK employees, as needed, move easily over the roller balls for quick delivery to the autoclave.

ATK has three autoclaves, all supplied by ASC Process Systems (Valencia, CA, US). Two are 18.3m long and the third is 26m long. Three more are expected soon, and will accommodate manufacture of stringers and frames for the A350-1000. Each autoclave, says Milenski, can accommodate 40-45 stringer molds.

Frame manufacturing at ATK operates on principles similar to those that drive stringer fabrication, but a frame's curved z-shape introduces some new complexities. Also developed in-house, ATK's ASF framemaking machine, designated ASFM-R, is oriented around a donut-shaped steel rotary table that rests horizontally on the shop floor. Over the table is a large blue gantry, on which are interchangeable tape-laying heads and a forming station. The tape heads are exchanged on the ATK gantry by a robot from KUKA Robotics (Shelby Township, MI, US). An RFID-tagged frame mold is secured to the table, which then rotates to the tape-laying station, where Hexcel carbon fiber prepreg tape is placed by the ATK gantry. The robot chooses tapes from several feed heads loaded onto the gantry, applying tapes of varying widths and orientations, depending on the tool type. When the layup is complete, the table indexes to the forming station, where tapes are compacted.

For some frames, says Milenski, 0° plies are preformed separately on a cutting table and then placed in the tool by hand before automated tape placement begins. These *rainbows*, as they're called, are formed using an Electroimpact (Mukilteo, WA, US) automated fiber placement (AFP) machine outfitted with a head that can simultaneously place up to 16 6.4-mm wide tows. The AFP, says Milenski, "places the rainbows and then cuts a border around them with an ultrasonic knife." The vacuum table, also made by Electroimpact, features a zoned vacuum system, which holds the rainbows in place during layup. Each rainbow preform is only one ply thick; each frame requires between 12 and 36 of these 0° plies.

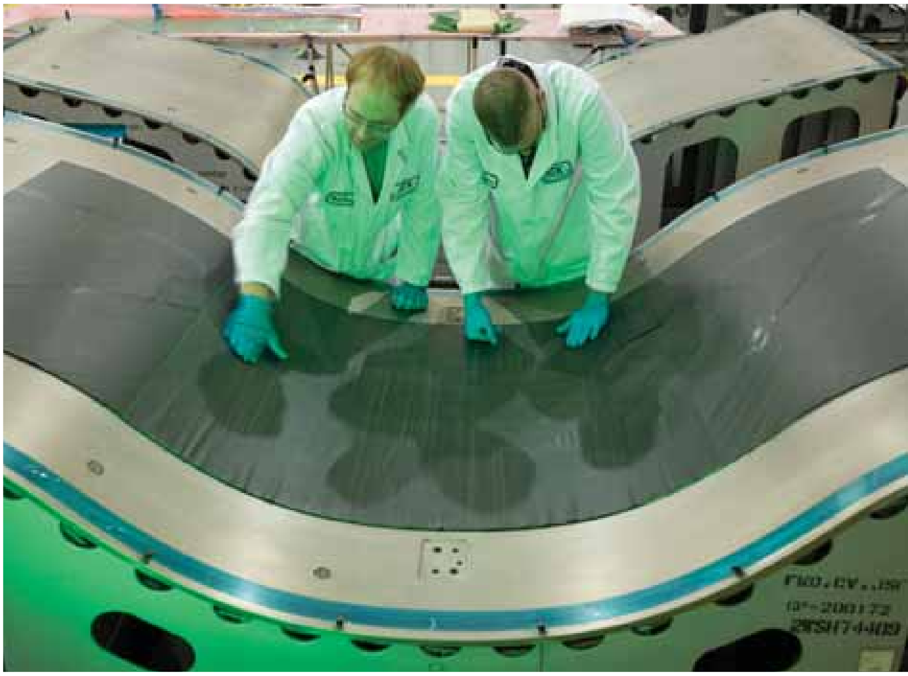
Nondestructive inspection (NDI) of all stringers and frames is done on an ATK-designed and -built phased array system. The company also uses a proprietary linear NDI system.

High-performance AFP

As the tour moved on, it became abundantly clear the MPM and ASFM are simply the latest in an impressive series of technology adaptations behind ATK's success. Second only to stringer and frame activities, ATK's most active manufacturing process in Clearfield focuses on automated fiber placement (AFP). And it's no wonder: ATK developed the *first AFP process* in 1982, and has been fine-tuning it since.

As an AFP pioneer, ATK maintains several AFP machines that were developed in-house. In Clearfield, four of its seven AFP machines are ATK-made, two others were built by Fives Cincinnati (Hebron, KY, US) and one more was supplied by Electroimpact (see Table 2, p. 41). The latter, noted earlier, is used to make arched stack-ups for fuselage frames. Across all US locations, ATK operates 15 AFP machines — five built in-house, one from Electroimpact and nine others from Fives Cincinnati.

The largest AFP parts manufactured in Clearfield are the carbon fiber/BMI wingskins for the F-35 *Lightning II*. Fiber placement machine (FPM) 2, as it's called, is used for the job and features a 27,216-kg multi-station mandrel and a 32-tow head with seven axes of motion. The "multi" designation accounts for what happens



Automated Tape Laying and Inspection

ATK's in-house-built ATL systems are large and complex. Each features a platform (left center in the top photo) on which the ATL head, material creel and operators ride as the system builds a laminate on the mold (at right in top photo). After ATL, ATK technicians use a Virtek laser inspection system to assess a BMI layup (bottom photo) for dimensional conformity, gaps and foreign object damage, among other parameters. Source (both photos) | ATK *after* a wingskin has been fully placed: The mandrel automatically rotates on a horizontal axis away from the machine head to be scanned by a Virtek laser projector system, which verifies the accuracy of dimensions, fiber orientation and ply boundaries, and checks for gaps and FOD.

Milenski says the BMI, supplied by Cytec Aerospace Materials, (Tempe, AZ, US), has proven particularly challenging to fiber place because of its low tack: "In my opinion, the F-35 nacelle is one of the hardest parts to fiber place that I know of." All the same, ATK has gotten pretty good at it. "Making a BMI ply at over 1,000 inches per minute *this* pretty?" says Milenski, pointing to a skin undergoing laser inspection. "I cannot reiterate how hard that is."

One reason for the difficulty, Milenski notes, is the OEM's strict skin thickness requirements. This entails frequent measurement of tools and laminates, and the presence of operators on the shop floor who, Milenski says, "are trained to verify quality." Ideally, a skin comes out of the autoclave within thickness tolerances, but if it doesn't, ATK must build up or machine away material.

During *CW*'s visit, ATK was in the process of completing buy-off of a new Fives VIPER AFP machine, designated FPM 5, that will work in tandem with another VIPER to make F-35 wingskins. The new VIPER features an operator platform equipped with a carbon fiber creel bank that feeds the placement head. The entire platform, with operator, "rides" with the placement head as it works on a mold. Milenski says the machine's laydown rate is 35.6 m/min, which he characterized as "a very big deal for BMI."

ATK's relationship with Fives, says Milenski, is one of close collaboration. So close in fact, that ATK was the first to use Fives' Dockable Gantry System (DGS), which *combines* ATL and AFP in one machine. The gantry-based unit's ATL head handles the large, noncomplex surfaces, and then — on the same mold — the machine's control system can switch, automatically, to an AFP head for narrow, more complex and/or highly contoured surfaces. The head-to-head transition takes less than 2 minutes. For that reason, the system is expected to optimize material deposition rates and increase manufacturing flexibility.

> ... continuing to develop new, high-volume automated composites manufacturing processes is the key ....

Back to the future

Although ATK has honed its fiber placement, tape laying and automation expertise to new highs for speed and precision, ATK continues to invest substantially in R&D, and isn't letting its past dictate its future. Notable on the horizon is its Automated Spar Forming (ASF) technology, which will *compete* with the ATL, AFP and hot-drape forming technologies used today to manufacture spars. ASF dispenses carbon fiber prepreg tapes into a female spar tool from one of four in-line rolls positioned over the tool. As tapes are laid, a series of rollers passes over the tool surface, providing compaction and debulk operations, working horizontal and vertical tool surfaces. The system can accommodate thickness changes across a spar and automates tapered joggles with ply drops. The benefits, says ATK, are reduced handling risk, good fiber alignment, consistent and tight radii, low void content, elimination of intermediate debulks, increased design flexibility and reduced material buy-to-fly ratio. A spar demonstrator manufactured by ATK shows the system's capabilities to meet a variety of flange angles, radiuses, thicknesses and fiber angles (see Table 3, on p. 41).

ATK also is pursuing out-of-autoclave (OOA) technology with its Ultrasonic Tape Lamination (UTL) system, which features ATL placement of thermoset- or thermoplastic-based prepreg tape (the former is cured in-situ, ultrasonically, at the tape head). ATK has demonstrated the process with prepregs from a variety of US suppliers, including Cytec's Cycom 977-2, HexPly 8552 and HexPly M21E from Hexcel and PEEK from an unidentified supplier. A cryogenic tank recently made with Cycom 977-2 epoxy had resin volume of 36.8% (vs. 37.2% for autoclave), fiber volume of 62.76% (vs. 62.8%) and void volume of 0.425% (vs. 0.006%).

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Also coming soon, ATK will roll out the MPM2, its next-generation Material Preparation Machine. ATK has partnered with MTorres (Pamplona, Spain) on this new machine. MPM2 will provide two new options: production of material up to 1.5m wide; and *tapering* of flag width to optimize material use, especially in spar fabrication applications (see MPM1 and MPM2 flag comparisons, top of p. 42.)

ATK's already-rich technological history and future promise that this firm will remain in the vanguard of composites evolution. As it seeks new ways to automate and streamline fabrication processes, the composites industry — particularly its aerocomposites arm — will continue to look to leaders who, like ATK, seek increasing sophistication in process integration and quality control at production rates unlike any the industry has seen. Milenski concludes: "ATK believes that continuing to develop new, high-volume automated composites manufacturing processes is the key to expanding the use of composites on aerospace structures while maintaining high-tech jobs in the US." CW

ABOUT THE AUTHOR

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Dark knights: Sleek trimarans surveil the seas

Epoxy-infused patrol boats outperform less nimble and more costly conventional naval craft.

» A response to the changing needs of modern navies with greatly reduced acquisition and operations budgets, the *Ocean Eagle 43* is a light ocean patrol vessel (OPV) that makes use of modern electronics for multiple missions — many of low intensity but high economic import, such as anti-piracy and surveillance of fishery, oil and gas and other maritime resources. Constructed of composites by Chantier Naval H2X (La Ciotat, France) for shipbuilder CMN (Paris and Cherbourg, France), the new 43.6m OPV benefits from CMN's 68 years of surface-combatant craft experience and construction of hundreds of advanced vessel designs for 38 navies around the world. Part of the *Ocean*

Sleek Patrol Boat

The 43m *Ocean Eagle* trimaran offers affordable naval mission versatility, including a helipad (see renderings), thanks to an efficient trimaran design actualized in composites by Chantier Naval H2X (La Ciotat, France). H2X' first finished composite trimaran shell arrives at CMN's Cherbourg, France shipyard (see p. 48) for finishing and outfitting with propulsion, mechanical systems, armaments and electronics.

Source (all images) / CMN

Eagle's versatility comes from its sleek and fast trimaran hull, which also offers a beam (width) that can accommodate a landing platform for unmanned aerial vehicles. A renowned shipyard in its own right, H2X's methods contribute to the trimaran's favorable performance-to-price ratio *and* have earned its builder the record for the largest hull ever infused with epoxy resin in one shot.

Designing for efficiency

Conceived by legendary naval architect Nigel Irens*, the Ocean Eagle 43* is a descendent of his multi-hull designs, which dominated international sailboat racing for decades. Predecessors include an Irens' *powered* trimaran, the 21.3m *iLAN Voyager,* which still holds the record, set in 1988, for circumnavigating Great Britain without refueling (2,523 km at a fast average speed of 21.5 knots on only 2,000 liters of diesel). A decade later, Irens' 35m trimaran, *Cable & Wireless Adventurer*, circumnavigated the globe, shaving 10 days off the 84-day record previously set by the U.S. Navy's nuclear submarine, *Triton*.

"It's taken many years for the world to warm up to this design for an efficient surveillance vessel," notes Irens, "but it is a perfect application for a trimaran." The long, slender main hull and diminutive outer hulls (called *amas*) provide exceptional stability but weigh less and experience less drag than other hull forms of comparable displacement, including twin-hulled catamarans. "The trimaran offers the greatest range … due to its very low wetted surface area," he explains. "What you get is a top speed of 30 knots for *Ocean Eagle*, but more importantly, a very economical 20-knot cruise for a 4,828 km range."

"The *Ocean Eagle*'s capability is to cruise efficiently for many hours, but then accelerate quickly and pursue," observes H2X's head of composites Pierre Lallemand. Its lightweight construction is key to its acceleration and long-range fuel efficiency. Rivoyre Ingenierie (Sophia Antipolis, France) assisted in completing the laminate design, which uses mainly glass fiber/epoxy sandwich construction. "Everything … is cored and infused," says Lallemand, "except for monolithic areas near the bottom of the hull at the front of the boat." Carbon fiber was used here as well as in high-load areas like stringer caps and in the arms that connect the amas to the main hull. "The composite structure is well proven," says Irens, "and essentially uses unidirectional reinforcements along the top and bottom of the 'shoebox' formed by the hull and deck." He adds that off-axis reinforcements (±45°) are used to handle the shear/torsion between the top and bottom.

> … Chantier Naval H2X now holds the record for the largest hull ever infused with epoxy in one shot.

Preparing for dark hulls

Destined for naval duty, the composite structure would be finished with standard dark gray paint, which reduces ship visibility on the horizon but also absorbs heat from sunlight. That made the glass transition temperature (T_g) of the resin a key concern. Here, H2X drew on its 20-year relationship with epoxy resin supplier Sicomin (Chateauneuf les Martigues, France) to define an appropriate matrix.

"The original T_g specified was 120°C to 140°C, a carry-over from the initial design which called for prepreg," explains Sicomin's export manager Marc Denjean. "However, that would have doubled the cost of the resin and also increased the cost of tooling and postcure." Fortunately, the design/build team switched to more economical resin infusion processing, for which Sicomin could suggest a system with a lower T_g of 90°C, based on its history with multiple dark-colored, epoxy-infused boat projects. Denjean points out that infusion epoxies with a T_g of 80°C are readily available, but he believes that »

1 Layup of biaxial and quadraxial fabrics, foam core (double-cut, to aid resin flow), and processing materials (peel ply shown here) into the 300m^2 main hull mold took roughly three weeks, but that timeframe was reduced by 20-30% in later boats thanks to core kitting services provided by Gurit (Isle of Wight, UK).

2 H2X takes few risks with such a large infusion. Vacuum bag preparation included the installation of many, closely spaced resin inlets, which were opened and closed during the infusion process, as needed, to encourage proper resin flow and discourage dry spots.

5 Stringers and bulkheads were bonded into the main hull, using wet layed glass fiber tapes and SR8500 laminating epoxy with Isobond SR1170 for high-stress areas, from Sicomin (Chateauneuf les Martigues, France).

3 Over a 5-hour period, 4,000 kg of epoxy resin was infused into the main hull. Vacuum was maintained for another 4 hours until gel was complete. Infusion of amas, arms, deck components and other parts (a total of 106) was done in parallel to save time.

4 After it was postcured for 16 hours in a 43m long by 15m wide oven at 60°C, the main hull was ready for assembly.

6 The 11m-long amas, infused in two halves, are shown here with bulkheads tabbed in place. They were joined at the centerline, using wet layup tapes and vacuum bagging.

7 The main hull, after stringers and bulkheads were in place, was fitted with the arms that connect the hull and the outboard amas.

10 The first fully assembled *Ocean Eagle 43* was rolled out of an H2X facility ready for delivery to CMN for outfitting — one of three that will be delivered to the Mozambique government this year.

Source (all step photos) / H2X | Photographer (#5, #6, #8) / Bertrand Santina

8 The main deck (made in three sections) and the pilothouse topped out the hull structure.

9 H2X crewmembers vacuum bagged wet layups on exterior assembly sites to optimize consolidation and, thus, increase impact and environmental resistance and reduce the need for surface preparation before painting.

is too low for dark hulls, risking not only print-through but a loss of mechanical properties over time that could result in laminate or structural failure.

Sicomin also gathered differential scanning calorimetry (DSC) and dynamic mechanical analysis (DMA) test data to support its confidence that a sufficiently high heat distortion temperature (HDT) would be achieved with the 90°C T_g resin, and that it would ensure that aging would not be a problem.

"With time, the T_g will decrease a little," Denjean explains. "This is what we refer to as the wet T_g, and it must stay above 80°C." Denjean recounts that Sicomin also asked H2X to make small samples per every batch of mixed resin during the actual infusion "which were then cured with the same history as the boat. These were tested using DSC and DMA to double-check T_g and ensure the mix ratio was respected." This also provided complete traceability for the molding processes.

Taking no chances

Despite the main hull's size, H2X did no flow modeling. "We don't take too much risk when we infuse," Denjean explains. "We use numerous feed points and short flow distances between them. But we did do a lot of infusion testing on a large glass table to ensure that all of the different cored laminates would infuse completely, without problems."

Corecell foam core from Gurit (Wattwil, Switzerland) was used in densities from 80 to 200 kg/m^3 and in thicknesses from 20 mm to 40 mm, optimized by location to save weight. "The glass table allowed us to see how the outside skin wet out and how the resin moved as well as the flow speed, which is a vital part of the resin mixing and feed-line arrangement calculations."

Lallemand and his team tested all of the laminate schedules — for example, hulls vs. floors and junctions between these and the superstructure. "There were many changes we had to make based on this testing," says Lallemand. "For example, some skins have 4,000g[/m^2] of fiber and there were issues with infusing these, so we changed the laminate plan, altering the direction of the fiber to achieve the flow and wetout needed — of course, with designer and naval architect approval." Here, too, Sicomin provided key assistance, »

developing 150-mm and 300-mm wide UD tapes especially for infusion of the critical arm structures. Stitching was designed to leave open paths that would encourage resin flow but was balanced to achieve sufficient fiber volume for the required mechanical properties. H2X used 10 layers of these tapes in the arms.

Tests also were run on the epoxy resin, Sicomin's SR8100 infusion formulation. "We had to test the hardener to ensure that we had the right viscosity and gel time," Lallemand recounts. "The goal is to have a viscosity low enough to permeate the laminate quickly, but not so quickly that you have dry spots. The gel time must be long enough to enable infusing the whole hull. But you don't want a gel time so long that there is too much time between completion of wetout and beginning of gel." This is because the team must still keep watch over the infused laminate under vacuum until gel is complete. Lallemand concludes that an excessively long gel time "wastes time and money and increases risk."

> ... with only 9 months to first boat delivery, testing had to be done in parallel with mold fabrication.

The epoxy-infused structures also would have to be postcured to achieve full mechanical properties. "We made lots of tests for gel time and exothermic peak temperature to make sure that the postcure process was correct." He notes that all of the above resin characteristics must be balanced but also must yield maximum mechanical properties and do so without postcuring at too high a temperature. Based on the testing, H2X elected to postcure at 60°C.

The *Ocean Eagle 43* trimarans were certified by the French classification society Bureau Veritas (BV, Neuilly-sur-Seine, France) to ensure they met rigorous engineering and quality standards. BV reviews drawings and laminate calculations to make sure the boat structure can handle the loads at its 30-knot top speed in open-ocean conditions. It then performs mechanical property testing on panels supplied by H2X to confirm actual properties. Tests included tensile strength and modulus, porosity and four-point flexure of sandwich panels, among others. BV also visited H2X weekly to inspect construction quality.

Making massive molds

Because H2X had only 9 months to complete and deliver the first boat to CMN, testing work proceeded in parallel with mold fabrication. Although flat panels could be made on a table, the main hull, the amas, and the arms and other curved structures required shaped molds, nine in total. H2X made its own tooling, having the ability in-house to go from CAD drawings to CNC-machined plugs to infused tools. The molds for this project, however, were built differently, formed directly (without a plug) from CNC-cut wood panels that were sheathed with plywood and composite laminates, and then surfaced with tooling paste and sealant. One issue was to ensure the mold was airtight. For previous large, infused epoxy yachts, H2X had simply CNC-cut molds from epoxy tooling board and then coated the surface for vacuum integrity. However, because the main hull mold surface area totaled 300m^2, H2X chose the more cost-effective wood construction, but had to adapt the surface treatment for the large size and then test it for airtightness. "We do this by putting the bare mold under vacuum and measure how much the vacuum level drops over 30 minutes." When it was satisfied with the molds' vacuum integrity, the team prepared for infusion.

Coordinating infusion

To keep overall construction time to a minimum, the hull, amas, arms and deck parts were layed up and infused in parallel. "We layup and infuse in a temperature- and » humidity-controlled cleanroom," says Lallemand. "For parts that would not fit here, we made temporary enclosures — 'cocoons,' which we could air condition and monitor." Temperature control, he explains, kept resin viscosity low, but not so low that the resin moved too fast. This helped them to avoid resin cure before infusion was complete, and it prevented generation of too much exothermic heat.

Because core materials for the first boat's main hull — the single largest infusion — were cut in-house, layup of its dry materials stack, including quadraxial and biaxial fabrics supplied by FORMAX (Leicester, U.K.) and SAERTEX (Saerbeck, Germany), took roughly three weeks. But core materials for the second and third main hulls were kitted by Gurit, reducing layup time by 20-30%. "We did not have enough time to do it elsewhere," says Lallemand of kitting, "but in the future we will try to do this more because it saves us time in preparing the infusion."

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According to Lallemand, organizing such a large infusion — almost 4,000 kg of resin for the main hull — was a challenge. "We had to coordinate the people, how to mix and feed the resin and where the points for this would be." Several mixing points were prepared along the main hull's length, and 10 technicians were stationed inside the hull to control resin flow. "They do this by opening valves at feed points, and then when the resin reaches a set point, they close the previous feed valves," Lallemand explains. "When they open the next feed valves, they check to make sure there are no leaks — which is the main issue — inspecting all of the feed line connections and ensuring there are no air bubbles."

"The core has a big influence on the infusion," Denjean contends. H2X used double-cut core, with very thin cuts on the top and bottom that help aid resin flow on both sides. They also used a micro-perforated release film, supplied by Cytec Industrial Materials (St. Jean, France) and distributor Diatex (Saint-Genis-Laval, France). "Thus, an infusion flow web is no longer needed," says Denjean. "In effect, you combine the peel ply with the flow medium, which is easier to lay down and reduces consumables." Sicomin supplied micro-perforated PVC foam, used for flat panels such as bulkheads, and provided the release agent used on all of the tools and molds.

The main hull was infused in 5 hours and vacuum was maintained for another 4 hours until gel was completed. This was followed by a 16-hour postcure in a 43m-long by 15m-wide oven at 60°C. The 11m-long amas were infused in two halves and then joined along the centerline. Other large structures included the main deck, the 6m by 15m helicopter deck, the pilothouse/bridge and the 5m-wide by 15m-long arms that connect the amas. "These two large parts are each essentially a box joining the main hull to the floats," says Lallemand. "The top parts were very complicated and also form one of the most stressed areas in the boat's structure, so quality here was critical."

Enabling assembly consistency

Following infusion and cure, assembly began. "There are 106 parts to assemble, all composite," says Lallemand. "It took several weeks to build all of the structure *inside* the main hull, including stringers, bulkheads, floors and decks." Parts were joined by conventional wet layup tabbing, using glass reinforcements supplied by Sicomin, similar to the carbon fiber tapes provided for the arms. Sicomin also supplied the SR8500 hand laminating resin for tabbing and Isobond SR1170 for enhanced bonding in high-stress areas. All of the connections on the outside of the hull were vacuum-bag consolidated after wet layup to optimize impact and environmental resistance and reduce surface preparation for painting.

"We made tests to minimize this assembly weight," notes Lallemand. "We asked laminators to make test joints and then we cut and tested these for weight and resin-to-fiber ratio."

Although assembly of the hull, arms, amas, deck and superstructure took three months, H2X's overall attention to process control paid dividends: The weights of the first and second boats' main hulls differed by less than 5 kg — impressive for such a large structure. "Within 100 kg would have been good," quips Lallemand, adding that each boat's complete composite structure weighs less than 30 MT.

Delivering versatility

The first three *Ocean Eagle 43*s will be delivered to Mozambique in 2015. CMN has been so pleased with the design concept that it introduced a minehunter version of the *Ocean Eagle 43* in Le Bourget, France, at the 24th International Naval, Defence & Maritime Exhibition (Euronaval, Oct. 27-31, 2014). The company says it now offers an "ideal" solution for navies seeking simple, modular and versatile platforms, which can be assigned not only to surveillance and minehunting, but a variety of other patrol missions. CW

ABOUT THE AUTHOR

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Composites Events

Jan. 26-27, 2015 — Cape Canaveral, FL, US
39th Annual Conference on Composites, Materials and Structures
http://advancedceramics.org/conference/expo

Feb. 3, 2015 — Amsterdam, The Netherlands
International CompIC Conference
www.netcomposites.com/calendar/compic-2015/1410

Feb. 3-5, 2015 — Palm Springs, CA, US
SPE Thermoset TOPCON
www.spethermosets.org

Feb. 25-27, 2015 — Moscow, Russia
COMPOSITE-EXPO-2015
www.mirexpo.ru

March 2-4, 2015 — Beverly Hills, CA, US
SpeedNews 29th Annual Commercial Aviation Industry Suppliers Conference
http://speednews.com/commercial-aviation-industry-suppliers-conference/registration

March 9, 2015 — Paris, France
SAMPE Europe Summit
www.sampe-europe.org

March 10-12, 2015 — Paris, France
JEC Europe 2015
www.jeccomposites.com

March 15-19, 2015 — Dallas, TX, US
NACE Corrosion 2015
http://events.nace.org/conferences/c2015/index.asp

April 13-15, 2015 — Cologne, Germany
8th International Conference on Bio-based Materials
www.biowerkstoff-kongress.de

May 4-7, 2015 — Atlanta, GA, US
AUVSI Unmanned Systems 2015
www.auvsi.org/events

May 14-16, 2015 — Atlanta, GA, US
Composites Pavilion – American Institute of Architects Convention 2015
http://convention.aia.org/event/homepage.aspx

May 18-21, 2015 — Baltimore, MD, US
SAMPE Baltimore Conference and Exhibition
www.sampe.org (click "events")

May 18-21, 2015 — Orlando, FL, US
WINDPOWER 2015
www.windpowerexpo.org/wp15

June 2-4, 2015 — Houston, TX, US
JEC Americas/Techtextil North America/Texprocess Americas
www.jeccomposites.com/events/jec-americas-2015-houston

June 16-17, 2015 — Stade, Germany
9th International CFK-Valley Stade Convention
www.cfk-convention.com

July 12-18, 2015 — Chengdu, China
ICCE-23, 23rd Annual International Conference on Composites and Nano Engineering
www.icce-nano.org

July 19-24, 2015 — Copenhagen, Denmark
ICCM20- 20th International Conference on Composite Materials
www.iccm20.org

Aug. 17-20, 2015 — Edmonton, AB, Canada
CANCOM 2015
http://cancom2015.org

Sept. 8-10, 2015 — Novi, MI, US
SPE Automotive Composites Conference and Exhibition (ACCE)
www.speautomotive.com/comp.htm

Sept. 15-17, 2015 — Louisville, KY, US
IBEX 2015
www.ibexshow.com

Sept. 15-17, 2015 — Amiens, France
SAMPE Europe Conference 2015
www.sampe-europe.org

Sept. 22-23, 2015 — Knoxville, TN, US
Additive Manufacturing 2015
allison@gardnerweb.com

Oct. 26-29, 2015 — Dallas, TX, US
CAMX – The Composites and Advanced Materials Expo
www.thecamx.org

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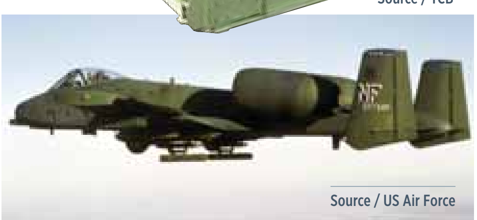
MULTI-MATERIAL RUDDER

Trailing-edge parts replaced in single-stage process

Source / TCB



Source / US Air Force

The US Air Force's A-10 *Thunderbolt II*, affectionately dubbed the "Warthog," is a Cold War-era Fairchild twin-jet introduced in 1977 for ground troop support, with rotary cannon that are ideal for attacking enemy armored ground vehicles. Although the Air Force has come close to mothballing the roughly 300 remaining Warthogs on many occasions, to free more than US$4 billion for use in the F-35 fighter program, the US Congress recently spared it again, possibly to assume a role in the current air war in Syria and Iraq.

Keeping Warthogs in the air is a challenge because the OEM no longer exists. Replacement parts have to be replicated. Particularly problematic is the rudder's trailing-edge control panel. "This is a part that the Air Force has been trying to procure for years," says Shelly Barlow, operations manager at TCB Composite (West Haven, UT, US). Several composites shops had tried but failed, previously, to meet the dimensional tolerances and minimum weight required by the Air Force. Because the part is a metal/composite hybrid, controlling the coefficient of thermal expansion (CTE) of the aluminum while maintaining straightness of the long, narrow part during typical multi-stage sandwich construction was the issue, Barlow explains. TCB, an AS9100-compliant shop, was able to land the contract thanks, in part, to its development of a one-step cure process, which enables TCB to control costs and meet the very demanding part tolerances at the stipulated finished weight of less than 6.4 kg.

The 0.5m by 2.2m rudder has a maximum thickness of 127 mm. Its 0.38-mm-thick outer skins of glass/epoxy prepreg and aramid honeycomb core — both from **Hexcel** (Stamford, CT, US) — are supported by an internal aluminum spar and aluminum ribs. The core is bonded to the skins with a film adhesive supplied by **Henkel Corp.** (Bay Point, CA, US), after TCB machines it to fit around the aluminum elements. A second, foaming adhesive from Henkel bonds the core to the aluminum. This complex combination is layed up in an aluminum tool that TCB designed and fabricated in-house. Proprietary "locating mechanisms" prevent the part's aluminum elements from moving during cure, ensuring part straightness. The part is cured in a 2.44m by 4.27m autoclave from **ASC Process Systems** (Valencia, CA, US), where pressure exerted by the spar and ribs under heat actually takes advantage of the aluminum/composite CTE mismatch to help consolidate the layup.

Says Barlow, "We were able to deliver the first article on time and have kept delivering remaining parts ahead of schedule."

BACK-COUNTRY BOATING

Carbon fiber ultra-lightens Adirondack pack canoe

Source / Placid Boatworks

For the true backcountry explorer, a strong but lightweight boat is essential — one that can easily be portaged lake-to-lake and stream-to-stream. To meet that need, Placid Boatworks (Lake Placid, NY, US) makes modern composite versions of classic, but relatively heavy, Adirondack pack canoes. At 3.6m long, its *Spitfire Ultra* single-seater can be double-blade paddled, like a kayak, and it weighs less than 8 kg (traditional pack canoes weigh 20 kg or more) yet can carry more than 136 kg.

"We wanted to create a solo canoe with the right balance between very light weight and ruggedness," says Placid owner Joe Moore, who credits success to vacuum infusion processing and high-performance reinforcements from **A&P Technology** (Cincinnati, OH, US). "We've applied large-vessel technology to a very small boat."

The canoe's outer hull incorporates a single ply of A&P's Bimax carbon fiber biaxial (±45°) fabric, backed by a plain-weave carbon fabric for the inside hull. A&P's QISO slit carbon fiber braid [0°/+60°/-60°] is used as a reinforcing layer between the Bimax and plain weave. Additional Bimax is incorporated into the bottom of the canoe. A&P's Sharx biaxial hybrid (carbon and aramid fiber) sleeving material, wrapped around Divinycell closed-cell foam from **DIAB (**DeSoto, TX, US), forms the canoe's gunwales.

The dry reinforcements are layed up in a female composite mold, built in-house, which is first sprayed with gel coat; white gel coat is used below the water line, and transparent gel coat everywhere else. Layup includes peel ply and resin flow mesh supplied by **Airtech International** (Huntington Beach, CA, US). Placid employs a reusable silicone vacuum bag and reusable vacuum plenums around the mold perimeter. The infusion resin is 8084 epoxy vinyl ester manufactured by **Ashland Performance Materials** (Columbus, OH, US). The canoe's four foam-cored thwarts, or crossmembers, are infused separately. Parts are cured at room temperature. After demolding the hull, Placid attaches thwarts and a composite seat with an adjustable back support and foot pegs, using methyl methacrylate adhesive supplied by **Plexus** (Danvers, MA, US). Moore says infusion ensures a "clean shop," reduces resin waste and produces consistent parts with very low void content and a better fiber/resin ratio than can be achieve with hand layup.

CAMX 2014 Product Showcase

At the inaugural Composites & Advanced Materials Expo (CAMX), exhibitors on the show floor offered a wide array of new technologies. The following are items not previously covered in the December 2014 issue of CW's predecessor *Composites Technology* (December 2014).

» MANUFACTURING

Polyurethane versatility

At CAMX, Bayer MaterialScience (Pittsburgh, PA, US) featured its usual full slate of products fabricated with Bayer's latest polyurethanes. Most notable were:

- A 3m section of a utility pole manufactured via filament winding process by RS Technologies (Calgary, AB, Canada). Polyurethane allows for a strong product that is much lighter than steel, making the utility poles easier to transport and erect.
- Romeo RIM (Romeo, MI, US) produced a 2.9m by 1.8m concept agricultural machine panel. Production parts also can be robotically inmold painted to customer specifications.
- Shipping pallets manufactured via pultrusion by RM2 (Luxembourg) are designed to replace wood with polyurethane. The polyurethane pallets are strong, durable, paintable and resistant to rot. www.bmsnafta.com

» PREPREGS

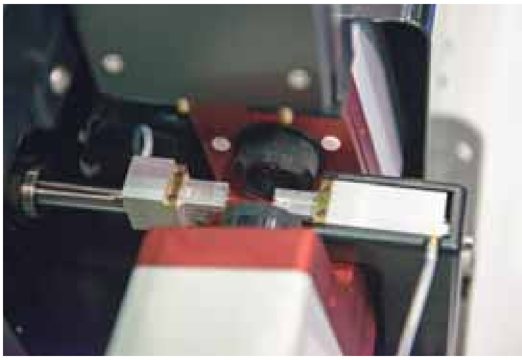
Polyurethane prepregs

Evonik Corp. (Parsippany, NJ, US) discussed with CAMX 2014 visitors its latest product, Vestanat PP, a polyurethane matrix system based on aliphatic diisocyanates for PU prepregs. The latent resin system is mixed and combined with the fabric reinforcement to form the prepreg, but doesn't react until processing temperature is reached. At that point, the isocyanates become reactive. Notably, the product is said to be stable at room temperature and requires no refrigeration. Further, its cure profile is reportedly tailorable to any process. Sub-2-minute cycle times are possible in compression molding processes, says the company. http://crosslinkers.evonik.com/product/crosslinkers/en/products-services/vestanat/pages/VESTANAT-PP.aspx

» TESTING & MEASUREMENT

Integrated fiber data system

Dia-Stron (Broomall, PA, US) introduced at CAMX an integrated measurement system for single fibers and filaments. The technology uses a combined laser diffraction and high-resolution extensometer measurement system (LDS/LEX) that reportedly combines measurement integration, precision and automation. It incorporates a high-resolution laser diffraction system with the linear extensometer force measurement unit, permitting the operator to collect dimensional and mechanical data in a single operation. The integrated measurement system is then combined with Dia-Stron's automated sample-loading module, which transports the samples from the loading cassettes to the measurement module. Dia-Stron also produces modules for fiber bending, fatigue and torsion. www.diastron.com



» FIBER REINFORCEMENT

Multiaxial noncrimp fabric

SAERTEX USA LLC (Huntervsville, NC, US) announced at CAMX that it has entered the multiaxial noncrimp fabric (NCF) market with the addition of 3D fabrics. SAERTEX 3D fabrics feature NCF in the 0° and 90° (x and y) orientation, as well as additional reinforcing fibers through the thickness — z fibers. These z fibers protect against separation, help speed infusion by promoting better resin flow characteristics and provide improved tensile and compressive strength. The fabrics are available in thicknesses from 1.5 mm to 3 mm and are delivered on rolls. SAERTEX 3D billets are thicker, ranging from 3 mm to 50 mm, with the same fiber architecture and can be delivered as flat parts. www.saertex.com

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See additional CAMX show coverage at http://short.compositesworld.com/CAMX14Rpt

MANUFACTURING SUPPLIERS

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ADVERTISING INDEX

Articulated composite booms extend reach of concrete-pumping arms

A 25% weight reduction vs. legacy steel yields economics that justify upfront cost of carbon fiber.

» As the use of composites has expanded over the past 70 years, one of their many benefits has consistently driven innovation: Composites enable manufacturers to design and build parts with the strength and stiffness of conventional materials but at significantly reduced weight. Such efforts have captured the "low-hanging fruit," to much applause, in huge markets — aerospace, boatbuilding and wind energy come to mind. No less important, however, are efforts by pioneers in niche applications that demonstrate, with little fanfare, the unlimited potential of the technology.

Prime examples are Italian construction equipment manufacturer Centro Italiano Forniture Alberghiere Srl (CIFA, Lomazzo) and composites fabricator RIBA Composites Srl (Faenza). Together they have developed carbon fiber composite booms for concrete-pumping machines. In full commercial production since 2011, the booms can be made in a variety of lengths.

Carbon fiber booms replace steel in the final sections of the mechanical arms mounted on trucks like this one to place pumped concrete in hard-to-reach locations.
Source / RIBA Composites

Cascading savings

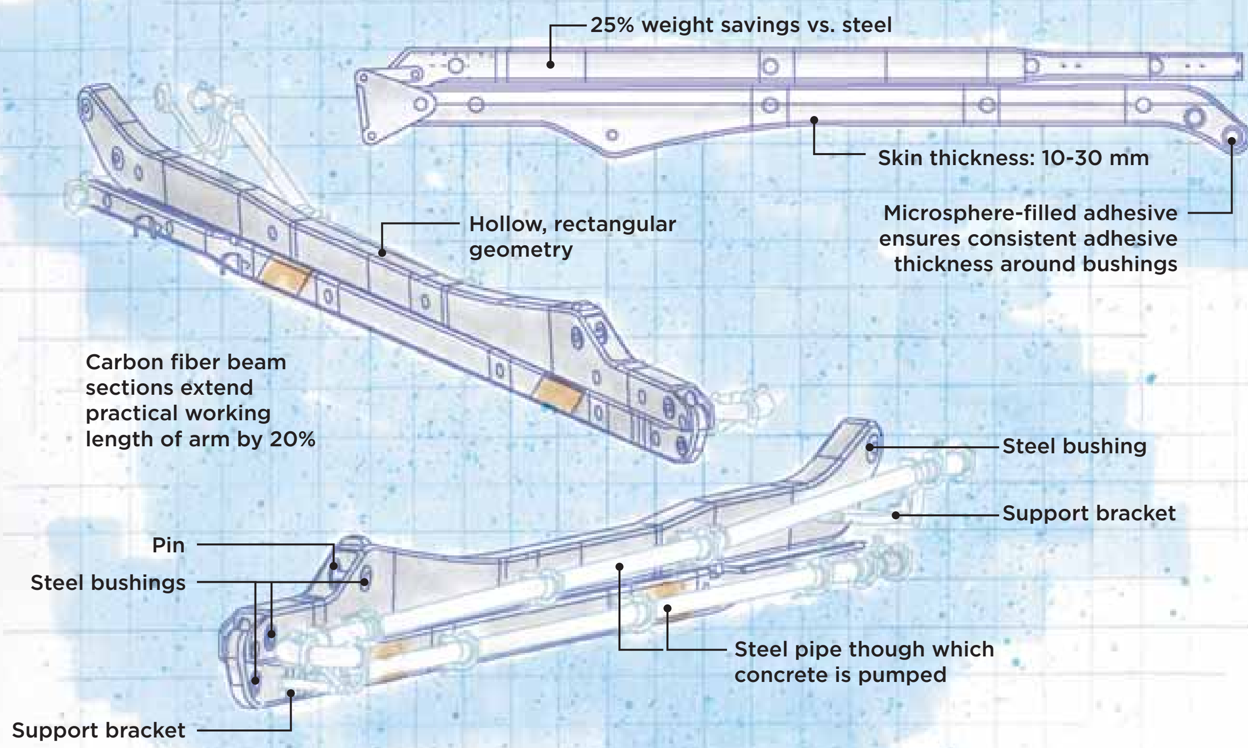
Mounted on trucks or trailers, concrete-pumping systems typically are fitted with articulating arms made of steel, which support the steel tubing through which concrete is pumped. Depending on site accessibility and the height of the concrete pour, the arm's end might extend hundreds of feet from the pump location. The greater the distance, the greater the moment of downward force that acts on the arm and must be counter-balanced at the truck or trailer. RIBA's carbon fiber booms replace the outermost segments of the arm where that force is greatest (see photo, p. 64) and realize section weight savings on the order of 25%. This opens the way to other benefits that justify the nominally higher cost of the carbon fiber. "The reduced weight means a smaller counterweight is needed," says Andrea Bedeschi, RIBA's general manager. In turn, the arm can be operated with smaller hydraulic cylinders and the entire system can be carried by a smaller, lighter truck or trailer, reducing initial investment and improving fuel economy. Additionally, a carbon boom extends the work length of the arm by as much as 20%. Finally, because scrutiny of and restrictions on truck weight are increasing, operators with oversized loads can face expensive surcharge levies or, in some countries, find themselves banned from roads. The lure of these potential benefits was the motivation for tackling the challenge of designing, making and selling a completely new part for an entirely new application.

Leveraging know-how

The chances for a commercially successful outcome to this essentially blank-slate project were bolstered by RIBA's experience in designing and building carbon fiber spars and masts for sailboats. "We are experts in building long tube sections," Bedeschi says. "The way we design and manufacture these booms is basically by applying the same principles for carbon fiber masts."

To prove project feasibility, RIBA conducted FEA modeling studies, using MSC Software's (Newport Beach, Calif.) MSC Nastran. According to Bedeschi, the effort entailed three key technical challenges, one related to design, another related to manufacturing and a third with an impact on long-term operation. A fourth challenge, market acceptance of a new paradigm in the construction industry, was mitigated, in part, by partner CIFA's buy-in to the project once feasibility studies were completed and costs, including ROIs, were evaluated.

The key to project feasibility was designing a laminate structure with stiffness similar to the steel benchmark, a daunting challenge given that the latter has a Young's modulus of about 207 GPa, vs. roughly 120 GPa for a PAN-based carbon/epoxy unidirectional laminate layer of the same thickness. In crude terms, this 40% stiffness deficit could be overcome by building up laminate thickness, but that would also build cost. FEA simulation enabled engineers to simultaneously assess laminate structures that would meet



DESIGN RESULTS **RIBA Composites' Carbon Fiber Arm for Concrete Pumping**

- Rectangular-shaped, hollow boom sections maximize strength-to-weight ratio, facilitating a 25% weight reduction vs. comparable steel booms.
- The ply schedule comprises three types of carbon fiber/epoxy prepreg with a wall thickness (up to 30 mm) that provides stiffness similar to steel, enabling the boom to handle static and dynamic loads.
- Steel bushings that connect articulating boom sections are bonded in place with an epoxy adhesive in which glass microspheres ensure an optimal, repeatable bondline thickness.

Illustration / **Karl Reque**

the stiffness criteria and explore the most cost-effective means to construct those laminates.

Each boom is subject to two primary loads: Static loads from the weight of the boom, the attached steel tubing and the concrete pumped through it; and dynamic loads generated in boom joints as the arm is moved. Simulation of both revealed that optimum boom strength-to-weight would be achieved by a hollow, rectangular geometry and a ply schedule comprising unidirectional 24K carbon fiber tape (with fibers oriented along the isostatic lines or stress trajectories), ±45° biaxial 24K carbon fiber prepreg, and ±90° woven 24K carbon fiber prepreg built up to a nominal wall thickness ranging from 10 mm up to 30 mm in high-load areas. All materials are impregnated with a toughened epoxy supplied by Saati (Legnano, Italy). The UD tapes, which account for ~50% of the laminate thickness, play a role in optimizing the structure's bending stiffness. The ±45° biaxial prepreg and ±90° woven prepreg each comprise ~25% of the total thickness, enhancing the structure's resistance to torque and damage respectively. RIBA sources its fabric, prepreg and fibers variously from Saati, G. Angeloni Srl (Venice, Italy), Toray Carbon Fibers Europe (Paris, France), Toho-Tenax Europe GmbH (Wuppertal, Germany) and Mitsubishi Rayon Co. Ltd. (Tokyo, Japan).

The FEA study also focused on joint construction, which would require some type of pinned connection. "There was an engineering concern about this feature of the boom design because of the reduced load-bearing capacity of composites compared to metal and the potential to damage the epoxy matrix in the joint area," Bedeschi recalls. Analysis suggested that 50-60-mm metal bushings would work *if* a way could be found to properly and reliably bond the metal components to the carbon/epoxy composite. Engineers devised a two-fold solution. First, to bond bushings to carbon/epoxy laminates, RIBA used Hysol epoxy adhesive, supplied by Henkel (Düsseldorf, Germany), in which the adhesive layer's bondline is controlled by glass microspheres, the diameter of which ensures an optimum, repeatable adhesive thickness, maximizing polymerization and shear strength at the

At 101m, this is the world's longest concrete pumping arm (a certified *Guinness Book of World Records* awardee). The final 50m of the arm (colored gray) is assembled from three composite booms molded by RIBA Composites. The longest boom, at 14m, weighed ~1000 kg, including 650 kg of carbon fiber, and was cured in a single autoclave cycle.

Source /RIBA Composites

Three types of carbon fiber prepreg are layed up in female molds, two tools (lower, pictured here, and a matched upper tool) per boom section. Molds are bagged internally and externally (below) and cured in an autoclave.

Source / RIBA Composites

bond. Second, the laminate at the joint interface is constructed of ±45° fabric, which reportedly reduces stress in the laminate at the joint surface. Extensive testing of laminate specimens was conducted in parallel with FEA to ensure that actual mechanical properties (in particular, stiffness) correlated with the simulations.

After testing validated the computer models, RIBA received approval from CIFA to build the first commercial boom sections for a concrete-pumping machine. They replaced the final two articulating sections — roughly half the total length of a 45m mechanical arm. Each section is about 11m in length. They do not replace the initial steel sections of the arm with composites because the cost vs. benefit tradeoff favors metals. Building the entire arm with composites would be cost-prohibitive.

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short.compositesworld.com/RIBAboom

Boom sections are molded in female molds. During layup, overlaps of 25.4 mm to 38 mm are created between adjacent plies of prepreg, per aerospace practice. The molds are joined at the laminate overlaps, creating a hollow tube. After layup, the molds are bagged internally and externally, and the bag materials are joined at the mold's open ends to form a single bag (see photos, above). During autoclave cure (at 6 bar), the vacuum pulled on the bag combined with the external pressure applied by the autoclave ensures optimal consolidation and strength-to-weight ratio in the laminate, yet avoids pressure-related deformation or alteration of the mold shape. "The pressure is acting on all the surface of the bag, internally *and* externally," says Deschi. "In this way we squeeze the plies without affecting the mold."

A final challenge was curing parts with walls as thick as 30 mm. Epoxy undergoes a robust exothermic reaction — the thicker the laminate, the higher the temperature. The risk is uneven heating of the mold and laminate layers, resulting in material degradation at the center of the laminate's through-thickness. Using a theoretical autocatalytic model, engineers predicted cure behavior as a function of temperature and devised a cure cycle with a cure temperature of 130°C and dwell steps that avoided exothermic peaks and resulted in homogeneous heating of the mold and laminate. Cycle duration, including cool down, is ~18 hours.

After cure, the demolded boom is CNC-machined on a 5-axis system, bushings are bonded into place and each section is inspected using a phased-array ultrasonic NDT system.

Since making its first 22m boom section set, RIBA's line of booms for concrete-pumping equipment has steadily expanded. The company now makes 10 different carbon booms for concrete-pumpers with arms ranging from 25m to 101m. Widths of booms can vary from 15 to 45 cm.

Last year, RIBA produced booms for 110 arms— about 250 individual booms, and Bedeschi expects a 10% increase in sales during 2015. That the booms have quickly made inroads into an inherently conservative industry is a testament to their highly functional design and benefits. CW

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