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CW Tours FiberCore Europe:
INFRASTRUCTURE INNOVATOR

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COLUMNS

» DEPARTMENTS

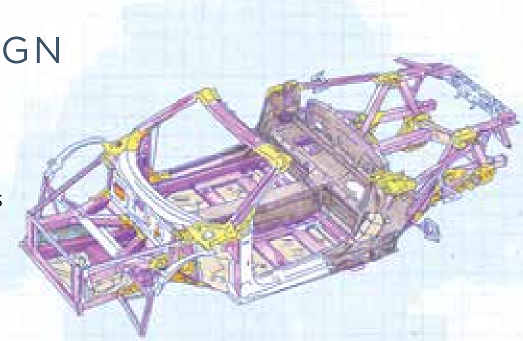
FEATURES

» ON THE COVER

FiberCore Europe (Rotterdam, The Netherlands) has produced more than 30 composite harbor bridges like this one just for the Port of Rotterdam this year alone, and that's a fraction of the 900 steel truss bridges in Rotterdam harbor that are suffering corrosion and deterioration. The company believes there's a need out there for composite bridges. The key is to build them well. Read more on p. 40.

Source / FiberCore Europe

FOCUS ON DESIGN



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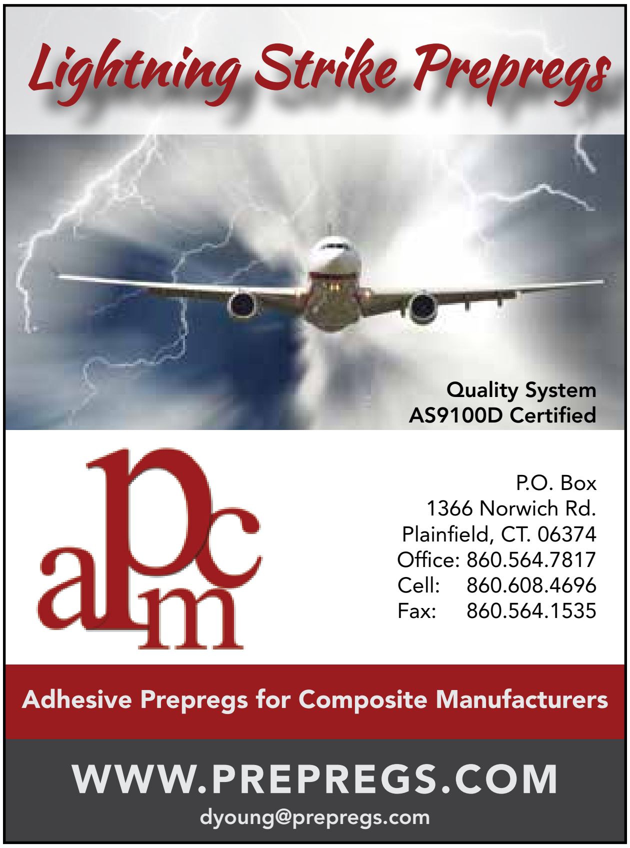

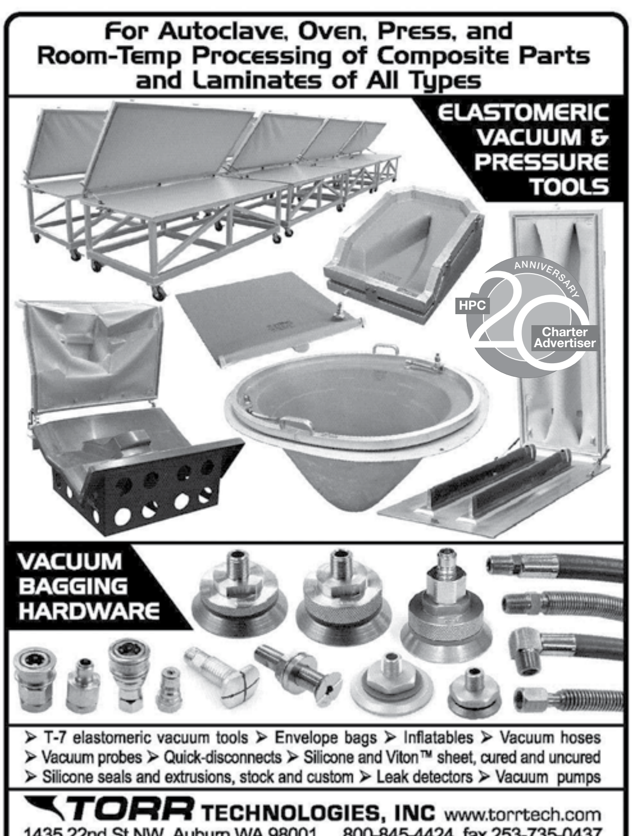

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It's December, a time for taking stock of the year that was, and for contemplating what the year ahead might have in store. Let's call it the State of the Composites Industry.

It is difficult to look about the world of composites today and not feel generally positive about the state of the industry. The composites-intensive Boeing 787 and Airbus A350 XWB are in full production and flying. The Boeing 777X, with massive carbon fiber composite wings, just started production and is expected to fly for the first time in 2019. The automotive industry is consuming composites like never before, with real plans for high-volume manufacturing. The recreational marine industry, which was so injured by the Great Recession, is on the mend and posting sales numbers not seen in a decade. The wind energy industry can't build composite turbine blades fast enough, and even the oil and gas segment is starting to put composites to greater use than ever. And in building and construction, we are seeing composites being embraced anew and applied in everything from structural building façades to elevator cables.

> Taking stock of the State of the Composites Industry.

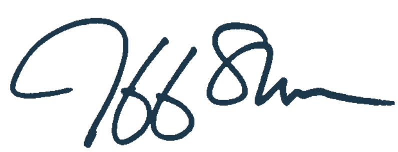
In materials and processes, the fast pace of innovation and creativity has stimulated new resin chemistries, new fiber sizings, new automation options, better preforming technologies, faster manufacturing processes, better process control, better quality control and better overall part quality. However, as with any good manufacturing environment, it is necessary to look for opportunities to improve and build efficiencies. So, as we enter 2018, what are our opportunities? Where can we improve and grow? Here's my two cents.

Accessibility. Robust, sustainable composites industry growth demands easy accessibility for designers and engineers from *outside* the composites industry. Right now, we don't have that. If you are an engineer used to working with metals or even unreinforced polymers, penetrating, entering and then comprehending the world of composites design and manufacturing is daunting. The complexities of myriad material types, tooling types and processing methods can pose a substantial barrier to entry and thus limits wider composites adoption. Improving accessibility requires education and at least some level of M&P standardization. Standardization, however, requires cooperation and planning on the part of people and organizations from throughout the composites supply chain. Such cooperation is happening, but, frankly, it cannot happen fast enough.

Automation. The composites industry grew up with the tradition of touch labor — people cutting fabric, placing plies, spraying chop, bagging molds, visually inspecting, trimming finished parts. With this came a certain amount of black art, and inconsistency. But as composites play on bigger stages (commercial aerospace, automotive), their manufacture must adhere to more stringent rules: Increased throughput, better process control, inline quality control. This means the human hand must go. There must be investment in robotics, automation systems and software to bring new levels of production discipline and efficiency. Capital equipment (and the associated expense), however, has never been this industry's strong point. We will have to make it a strong point soon.

Alternative materials/processes. This is an opportunity. Thermoplastic resins, additive manufacturing and non-PAN carbon fiber precursors are well positioned to trigger substantial change within our industry. Thermoplastics, although not new, have already proven themselves viable in aerospace and automotive structures, and that trend will accelerate. Very large, and getting larger, additive manufacturing systems are already reshaping (literally) how we make molds and tooling. Carbon fiber's big opportunity for growth is in nonaerospace applications. Several companies, not to mention government labs, are working on soon-to-be commercialized, low-cost precursors for nonaerospace carbon fiber that will likely facilitate expanded use of this material.

Do you have your own assessment of the state of the composites industry? If so, let me know at jeff@compositesworld.com. And have a great 2018.



JEFF SLOAN — Editor-In-Chief

Seeing the *C Series* deal in context: Borderless bargaining in a global marketplace

» On Oct. 16, Airbus SE (Toulouse, France) and Bombardier Inc. (Montreal, ON, Canada) jointly announced that they will become partners on the latter's *C Series* aircraft program (see our coverage of the deal in *CW* Trends, on p. 18). Airbus will acquire a slight (50.01%) majority interest in CSALP, the legal entity that actually builds the *C Series* planes. The *C Series* primary assembly line will remain in Québec, but additional *C Series* work will be added at the Airbus manufacturing site in Mobile, AL, US.

Although initially surprising, I'll argue here that it shouldn't be. It was yet another sign that in markets with global reach — air travel is certainly one — economic and competitive realities seem inevitably to take precedence over local politics and parochial loyalties. Consider first that this DEAL has enabled Airbus to *acquire*, rather than having to re-imagine, design and then build, a plane in the 100- to 150-seat range that is a fitting complement to its A320*neo* in a single-aisle passenger jet market for which Airbus is best prepared in the single-aisle market's higher end (150-240-seat range). Likewise, Bombardier, facing the daunting prospect of having to sell its *C Series* planes into a huge, expanding global marketplace dominated by Airbus and Boeing, now will have the strength and reach of the Airbus marketing machine behind its product, almost ensuring the *C Series* an enviable share of the lucrative single-aisle market.

And lucrative it will be. The single-aisle category, by all accounts will make up 60-70% of the global demand from airlines for commercial aircraft in the foreseeable future. And given the demanding production schedule that will no doubt result, Bombardier will be able to count on the Airbus supply chain to ensure materials availability and timely delivery, and to do so at significant *C Series* production cost savings.

Such international dealmaking isn't unprecedented, of course. Despite the current mood in the White House, much of US-based Boeing's (Chicago, IL, US) midsize, twin-aisle 787, for example, is made outside the US, because Boeing, too, despite strong "made in America" campaigns waged on the US political stage for decades, sought suppliers outside its "home" country to encourage sales of its groundbreaking composite-airframed jet, particularly in Japan and the then new and sure-to-grow air-travel market in China.

Whatever one might think of you-scratch-my-back-and-I'll scratch-yours dealmaking, it's a result of a political sensibility that sees beyond borders to the wisdom of rightly reading economic realities. It's about everyone wanting their share of the pie, to be sure. But that's not all it is. Ultimately, the goal, as Airbus CEO Tom Enders declared at the time of the Airbus/Bombardier announcement, is "a win-win for everybody!" For the composites industry, this sort of international web-building certainly has been a win. It's spread our technology to places it might not otherwise have gone, or not nearly so quickly as it has. It's done so at a technologically high level as well. And it's one very big reason why composites have progressed, in two short decades, from a largely Western European/North American game to a worldwide phenomenon.

This is not to say that companies like Bombardier and Airbus are immune to nationalistic influence. Both are, in fact, the beneficiaries of substantial native governmental subsidies — a fact that has aroused the ire of competitor Boeing, which does not so benefit. Boeing, however, has made news in recent years for how little it has paid in US corporate income taxes (seen by critics as a subtle form of governmental subsidy).

Yet it is difficult, in the context of the "borderless" global economic expansion we've witnessed, to imagine how cries of "America First!", "Brexit!" and threats of tariffs and trade pact pullouts that pit peoples of one location or conviction against those of another offer much beyond sensational news footage and discord. Protectionism and nationalism, political stances that earned mixed reviews at best (and helped incite major warfare at worst) in their 20th Century incarnations, appear in this light not only unwise in the 21st Century but plainly counterproductive, not only for the aerospace industry and other global enterprises, but, more to our point here, also for the composites industry.

One need only consider the disconnect between the current US government's desire to build a wall between Mexico and the southern US, and this country's (and others') business communities' active investments in Mexican communities to develop new manufacturing bases, particularly for commercial aircraft. (One of many *CW* reports of such activity, an example from 2015, was titled, significantly, "GKN Aerospace Mexico facility gains Nadcap accreditation.")

My point? Where markets are growing, those who flourish within them increasingly see national borders and political systems as challenging but negotiable obstacles on the way to global manufacturing and product sales arrangements that benefit all involved parties. Whether that appeals to one's political preferences or not, it appears to be the source of more jobs in more places — that's certainly been true in the composite industry — with far less discord than the alternative.

For details of the Airbus/Bombardier partnership arrangement, see CW's *full coverage online at the* CW *News site* | **short.compositesworld.com/AirbusCSer** CW

ABOUT THE AUTHOR

Mike Musselman is the managing editor of *CompositesWorld* magazine. He joined the *CW* staff in 2001 after beginning his career in journalism in 1985 as a technical writer and honing his craft as an associate editor and editor of two other international publications. **mike@compositesworld.com**

Tooling: 3D printing's "killer app"

» Recently, I attended the Additive Manufacturing Conference in Knoxville, TN, US, hosted by *CW* parent organization Gardner Business Media (Cincinnati, OH, US). It was evident, there, that great strides are being made in this technology's advancement. What was on display and discussed was almost all 3D printing technology. As I mentioned in this column in August 2015, "all 3D printing is, indeed, additive manufacturing; but not all additive manufacturing is 3D printing." I still struggle that these are conflated terms, because one is, technically, a subset of the other, but I'll put that aside because I believe 3D printing/additive manufacturing has great potential in the composites industry.

3D-printed metallic structures, especially those for the low-volume and very convoluted shapes found in jet and rocket engines, seem to be a perfect fit. Excellent properties are obtained in these parts, and the ability to embed flow channels and other geometrically complex features provides real value in replacing machined or cast metal parts. Although some companies are employing polymer-based 3D printing to build end-use components, I don't foresee 3D printing achieving the strength-to-weight ratio necessary to replace continuous fiber-reinforced composites on a mass scale. Likewise, in high-volume parts, it would be hard for 3D printing to displace discontinuously reinforced materials (SMC or long-fiber thermoplastics) given the short cycle times achieved today.

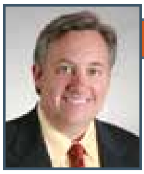
> If 3D printing can be scaled to make tools for composite auto body panels … it will be transformative.

That doesn't mean there isn't a place for this technology in the advanced composites market. Two companies, Cincinnati Inc. (Harrison, OH) and Thermwood (Dale, IN, US), are selling large, extruder-based polymer additive machines able to print parts more than 6m long, and Ingersoll Machine Tools (Rockford, IL, US) is developing a system targeted at parts up to five times this size. Several service bureaus have been established to supply large, printed polymer parts to third-party customers. Software suppliers have been active, with slicing programs that create print paths and applications that can perform topology optimization and predict polymer crystallization, cooling rates, residual stress and part warpage. So, for low volumes and lightly loaded structures, there are likely to be plenty of needs to fill.

And 3D printing's unique ability to cost-effectively realize one-off, custom designs suggests that this market's killer application will be tooling for making composite parts, rather than the parts themselves. It's already happening on the aerospace side. In 2016, Oak Ridge National Laboratory (ORNL, Oak Ridge, TN, US), in cooperation with The Boeing Co. (Chicago, IL, US), printed a 5.3m long trim-and-drill fixture for the 777-9 program from carbon fiber-filled ABS, which weighed 750 kg. Built in 30 hours, using a machine from Cincinnati Inc., the tool is listed by the *Guinness Book of World Records* as the world's largest solid, 3D-printed item. Although this trim tool operates at room temperature, ORNL has produced tools in high-temperature carbon fiber-filled polymers, such as PPS, which are able to withstand the 7-bar/175°C environment of the autoclave. At the conference in Knoxville, Thermwood displayed a carbon fiber-filled polysulfone (PSU) tool, along with parts produced from it via autoclave.

Nonaerospace applications also present opportunities. In 2016, TPI Composites (Warren, RI, US) received a contract from Sandia National Laboratory (Albuquerque, NM, US) to fabricate a limited number of 13m-long wind turbine blades for testing. Given that conventional machined plug/layup tooling processes can take 6 to 12 months, TPI worked with ORNL to print modules from carbon fiber/ABS, then connected these and applied layers of fiberglass/epoxy and a finish coat to manufacture the tools in less than half the time and at lower cost. The tools include integrated hot-air heating channels, replacing the typical resistive electric wire heating. Purdue University has printed small compression molding tools using thermoplastics that are able to withstand 500-psi and 175°C, and is designing tools able to make 10-50 prototype parts via compression and injection molding, and RTM.

Back in the 3D metal-printing world, ORNL, working with Wolf Robotics LLC (Ft. Collins, CO, US), has deployed a large-format, robotic welding-like process to manufacture a steel arm for an excavator. A new project, initiated by the Institute for Advanced Composites Manufacturing Innovation (IACMI, Knoxville, TN, US), with ORNL, seeks to leverage the Wolf Robotics innovation to develop metallic tooling for high-rate processes, with similar longevity to conventional tool steels, and more than 50% reduction in fabrication time and cost. With the potential to incorporate conformal heating and cooling, and to modify the tool quickly, this technology could be truly transformative if it can be scaled to make production tooling sized for automotive parts like body panels and floor pans. It's not a question of if, but when. CW



ABOUT THE AUTHOR

Dale Brosius is the chief commercialization officer for the Institute for Advanced Composites Manufacturing Innovation (IACMI, Knoxville, TN, US), a US Department of Energy (DoE)-sponsored public/private partnership targeting high-volume applications of composites in energy-related industries. He is also head of his own consulting company, and 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. He also served as chair of the Society of Plastics Engineers' Composites and Thermoset Divisions. Brosius has a BS in chemical engineering from Texas A&M University and an MBA.

Composites Fabricating Index smashes old record

October 2017 – 59.8

» Registering 59.8 for October, the Gardner Business Index (GBI): Composites Fabricating set an all-time high during the month. This latest reading raised the 2017 average for the Index to 55.1 for the year to date. October's reading was well above the third quarter average reading of 54.6. For the year-to-date and 12-month periods, the Index is up approximately 10% and a sizable 18.5%, respectively. The Gardner Intelligence review of the underlying data for the month indicates that the New Orders, Production, Employment, and Supplier Deliveries subindices lifted the overall Composites Fabricating Index higher while Backlogs and Exports subindices tended to hold the Index down. No components of the Index, however, showed contraction (a reading of <50.0) during the month as even Exports posted its strongest expansionary reading of the year.

The numbers for New Orders and Production both increased significantly during October. The growth in New Orders outpaced Production, which resulted in a significant and, consequentially, record-breaking reading in the Backlogs measure. CW

ABOUT THE AUTHOR

Michael Guckes is the chief economist for Gardner Intelligence, a division of Gardner Business Media (Cincinnati, OH US). He has performed economic analysis, modeling and forecasting work for nearly 20 years among a wide range of industries. Guckes received his BA in political science and economics from Kenyon College and his MBA from The Ohio State University.
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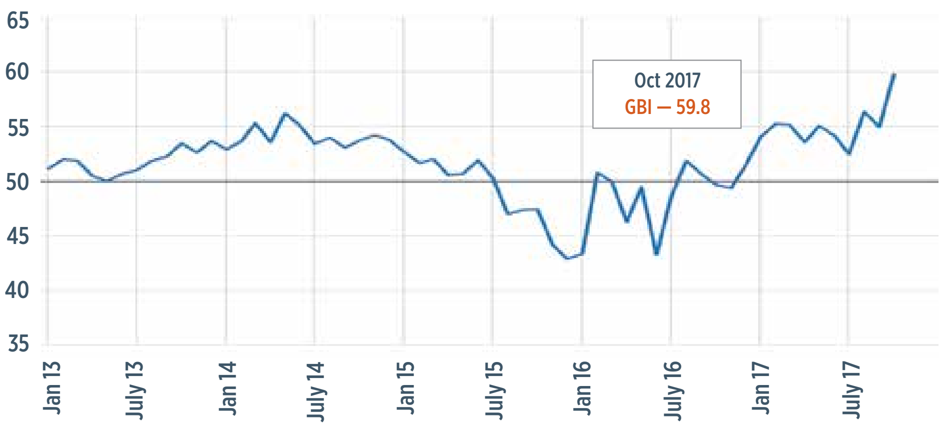
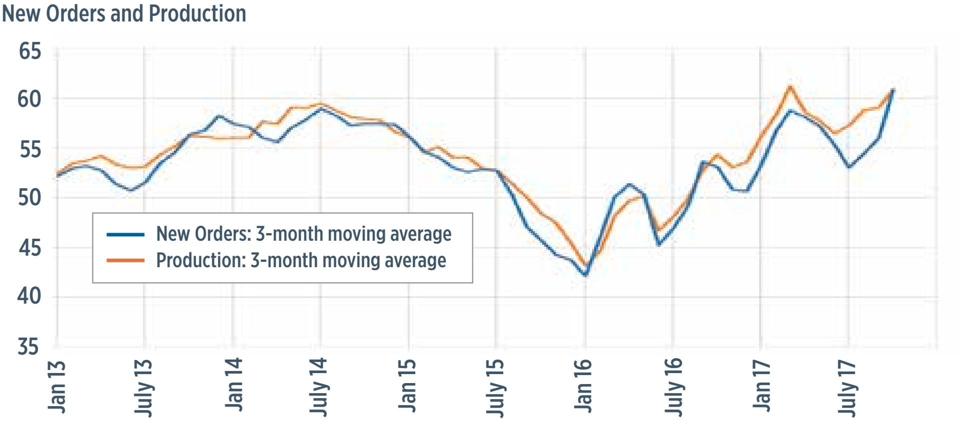
GBI: Composites Fabrication



■ Composites Fabricating Index shows industry on record-setting run

The Composites Fabricating Index is on track to register readings high enough to make 2017 its best year since the Index data has been recorded, edging out the records set in 2014.

New Orders and Production



■ New Orders and Production readings continue to climb

Readings for New Orders established a new high going back to the inception of the survey while Production tied its all-time high reading, which has been reached only twice before. Both of these record readings occurred this year.

An excerpt from the *CW Talks* interview with Clemson University's Joseph Choma, a composites shift at a major automotive Tier 1, and 3D printing goes big with plugs and molds for boat hulls.

Q&A: Joseph Choma, assistant professor of architecture, Clemson University

Editor's note: CW *Talks*: The Composites Podcast *features interviews with composites industry thinkers and doers. This Q&A is excerpted from Episode 9 of CW Talks in which Choma discusses his development of foldable composite structures for use in architecture, building and construction applications. Choma is very new to composites, but eager to use them sensibly. Catch the full interview on iTunes or Google Play or at the CW Web site |* www.compositesworld.com/podcast. *View a video of Choma's work |* short.compositesworld.com/Choma

***CW:* How do composites factor into your architectural discipline?**

JC: I was just trying to understand what fiberglass wanted to be and if we could find new, alternative approaches to the material. So, it was less about problem-solution and more about finding the most number of possible solutions.

***CW*: What surprised you most as you learned about composites?**

JC: When I was looking at structural applications of the status quo, carbon fiber and fiberglass is commonly compared to steel, and the way they compare it is they produce I-beams, which are an extruded or protruded logic. And then they essentially do a destructive test. But to me, I looked at this material that came to my hands and I was holding a textile, a piece of cloth, a surface. And then I would see resin. And to me it starts out as a surface. Why would anyone want to make an extruded logic or a pultruded logic? It wanted to be a surface logic.

***CW*: Out of this you developed the idea of folding composites. Explain that.**

JC: Again, fiberglass starts out as a cloth, which is a surface or a plane. And a piece of paper is a surface or a plane. I was interested in how you can translate the idea of folding something into folding fiberglass. And with that, if you just try fold a cloth, it has too many degrees of freedom. And if you resin a piece, you can't really fold that either. It's like a piece of glass. So, then I started looking at things like fabric hinges used in furniture applications. So, I realized that if I selectively coat part of the fiberglass to create a crease pattern, I can create fabric hinges for the structure to fold along. Eventually that led to a technique that allows fiberglass to fold like paper, without a mold.

***CW*: You tape off the seams to create the foldable dry sections of fabric, right?**

JC: That is correct. You can fold along wherever the tape was, so it is a very simple and intuitive technique. And then after you essentially have folded it in place, there are multiple opportunities for what you do with the seams. Do you apply resin to the seams after it's been deployed so it becomes completely rigid? Do you apply something like silicone to the seams which would then be waterproof, but still allow it to fold? Do you apply a B-phase resin on the seams where it would change its rigidity when it's exposed to UV light or heat?

***CW:* This also creates an easily transported material as well, right?**

JC: Yes. You can imagine a giant crease pattern of fiberglass cloth, you tape it off, apply the resin where you need to, you fold it, you flat-pack it, you ship it to the site, you deploy it, it becomes a large structure. After it's deployed, again, you decide if you apply resin to the seams . . . Essentially, after that, you have one, continuous long-span structure that's seamless — no molds, no material waste, no fasteners.

***CW:* This might change prototyping as well, because you could use folded paper to prove a concept.**

JC: Absolutely. The way that I am working, there is always going to be some kind of paper mock-up, and the paper model seems to translate quite directly to the fiberglass model. In addition to that, you can do some digital simulations where you can start to analyze with finite element analysis what's in tension, what's in compression, so we can start to predict ahead of time where we might need additional reinforcement and where we don't.

***CW:* Is there an analog in architecture to this idea?**

JC: I don't think so. I mean, you could think about thin-shell concrete structures, or just shell structures in general as one way to think about something, but those require intense form works to produce. So, again, this is a very different way of thinking. It's so economical on one hand, but on the other hand so much of it is embedded in the crease pattern and how that influences the three-dimensional shape. So, it really becomes more of a geometric problem, and how you engineer the material and where you place certain materials on that geometry to resolve the structure.

AUTOMOTIVE

Major automotive tier supplier moving to composites

A well-known Tier 1 supplier to the auto industry, Cooper Standard (Novi, MI, US) employs more than 30,000 employees at 120 facilities worldwide, and is the largest global supplier of automotive sealing systems. It also produces fuel and brake systems, fluid transfer systems and anti-vibration systems (AVS). And the big news is

Source | Cooper Standard

that in the AVS category, Cooper Standard is undergoing a significant materials shift from well-established, legacy metals to composites.

"These are big, sturdy traditional parts that have been made for more than half a century," notes Joe Emmi, Cooper Standard VP and managing director global AVS, referring to AVS body, strut and engine mounts typically formed from cast aluminum, stamped steel and rubber. "Our corporate mission is to innovate and provide superior products," he points out, "and thanks to advances in material science and design, the composite parts we've developed can now pass all of our tests."

He calls out three factors that have motivated Cooper Standard's move to fiber-reinforced plastics:

1) A growing demand from consumers for more comfort (in this case, less vibration) in both cars and trucks.
2) A need to reduce weight for OEMs for both better fuel economy and to accommodate more amenities.
3) A growing acceptance from OEM customers for new structural composite part designs, *if* they can meet performance criteria.

The criteria are substantial for these structural parts. For example, Emmi explains that body mounts, which attach a passenger vehicle's body to the structural frame, come in two types: conventional steel and rubber mounts and hydraulically damped mounts. The hydraulic mounts conduct fluid between two internal chambers to develop damping and improve the ride response of the vehicle. These mounts have typically been developed using stamped steel or cast aluminum housings, but they have now been replaced with composite plastics: "We converted one of our hydro mounts, originally a rubber sleeve inside a steel housing, to *(continued on page 14)*

BIZ BRIEF

Toray Industries Inc. (Tokyo) will open its Automotive Center Europe (AMCEU) in August 2018 near Munich, Germany, as part of a plan to strengthen its R&D function in Europe related to what it calls its Green Innovation (GR) Business Expansion strategy.

Toray aims to implement the Green Innovation strategy through development of new materials, building methods and structures required for environmentally friendly transportation equipment, such as electric vehicles, jointly with major customers (OEMs and Tier 1 companies) and to achieve environmental restriction goals, which are becoming stricter, and contribute to the realization of a low-carbon society.

The AMCEU facility (offices, laboratory and showroom), will have a floor area of 3,400m^2. In 2008, Toray established an Automotive Center (AMC) in its Nagoya Plant that has driven proposals, technology development and commercialization of solutions using new materials in league with Japanese automotive OEMs. As a result, Toray Group's net material sales for automotive applications grew about 10% per year from fiscal year 2014 to 2016, compared with 2% annual growth in global automobile production.

Building on the experience with AMC, AMCEU will reportedly attempt to play a similar role with similar results, offering core technology development assistance to automakers in Europe.

Toray says the AMCEU would act as a core technology development base in Europe, offering one-stop service to customers.

(continued from page 13)

a glass-reinforced nylon composite." He points out that in addition to saving significant weight, the composite housing meets customer performance requirements. "These are critical parts that must secure the body firmly to the frame," he adds. "Our customer understandably was a bit worried about the composite design, but we have demonstrated that it works."

Another example in composites, also developed under Cooper Standards' DynaFib Innovation Program, was conducted in partnership with a university and a composite materials supplier for a European OEM. In this case, says Emmi, "the strategic effort was aimed at advancing the *process* as well as the material and part design." DynaFib sought to extend the applicability of plastic bracketry by providing increased tensile strength at a significant mass savings. The group worked with Coriolis Composites (Queven, France) on an automated process that loops a continuous glass/thermoplastic fiber over two torque isolation mounts, with the continuous fiber designed to handle peak engine torque loads. The loop and mounts are then overmolded with polyamide. Emmi explains that the composite torque strut mount, designed to work within an engine mount system, weighs 50% less than the legacy aluminum part, and offers better tensile strength than a metallic solution. We're targeting introduction on a 2019 model year vehicle." He adds, "We're replacing metals with composites in our AVS business in parts that require high tensile strength, like brackets, torsional displacement arms and strut mounts."

CW MONTH IN REVIEW

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

Solvay acquires European Carbon Fiber GmbH
The strategic acquisition enables Solvay to develop a portfolio of large-tow carbon fibers to complement its existing pitch and PAN aerospace grade carbon fibers.
11/07/17 | short.compositesworld.com/SolvayCF

Boeing HorizonX invests in Gamma Alloys
Gamma Alloys is a leader in aluminum alloys, focused on developing advanced metal-matrix composites for use in aerospace.
11/06/17 | short.compositesworld.com/BoeingMMC

AC&A acquires Applied Composites Engineering
US-based Applied Composites Engineering (ACE) manufactures composite parts and structures for the aerospace and defense markets.
11/06/17 | short.compositesworld.com/AC

Toyota fuel cell bus features carbon fiber composite roof
Toho Tenax carbon fiber and aluminum are combined in fabrication of roof for Toyota hydrogen-powered bus.
11/06/17 | short.compositesworld.com/FCBus

Chomarat invests in a carbon multiaxial technology
This new multiaxial machine for the company's C-PLY product is reportedly 10 times more productive than the previous generation of machines.
11/06/17 | short.compositesworld.com/C-PLYmach

Orbital ATK wins contract to make composite parts for F-35
It has received an initial US$24 million contract from Lockheed Martin to produce composite bullnose and blade seals at its facility in Clearfield, UT, US.
10/30/17 | short.compositesworld.com/OATK-F35

Irkut *MC-21* flight-testing continues
The *MC-21-300* test aircraft, featuring an out-of-autoclave carbon fiber wingbox, flew 4,500 km from Irkukst, Russia to Moscow.
10/30/17 | short.compositesworld.com/MC-21test

Boeing begins 777X production
Production kicked off in Everett, WA, US, with a company ceremony on Oct. 23. The "reveal" included a video of the composite wing spars.
10/30/17 | short.compositesworld.com/777Xon

US wind power booming
US wind projects, as of the end of the third quarter of 2017, had reached 29,634 MW, the highest level since this statistic was first measured.
10/30/17 | short.compositesworld.com/AWEAstats

Airbus A330neo completes maiden flight
Airbus' newest jet, the A330-900neo, successfully completed its first flight on Oct. 19, when it landed at Toulouse-Blagnac, France.
10/30/17 | short.compositesworld.com/A330neoup

MARINE

Additive manufacturing for marine tooling


Source | Thermwood Corp.

A 3D-printed boat hull pattern has been completed using a near-net shape additive manufacturing process, and a production-capable fiberglass mold has been successfully pulled from the pattern, in a collaborative proof-of-concept joint evaluation program conducted by Thermwood Corp. (Dale, IN, US), Techmer PM (Clinton, TN, US) and Marine Concepts (Cape Coral, FL, US). On display at the AM2017 Additive Manufacturing Conference, held Oct. 10-12, 2017 in Knoxville, TN, US, the pattern was 3D printed slightly oversized, over a period of approximately 30 hours, and subsequently trimmed to final net size and shape, using Thermwood's trademarked Large-Scale Additive Manufacturing (LSAM) system. The printed material was Techmer's trademarked Electrafil ABS LT1 3DP, which reportedly has proven suitable for marine tooling applications when processed using LSAM print technology. The entire print, assembly and trim process reportedly required less than 10 working days to complete.

The final tool was printed in six sections, four major center sections with walls approximately an inch-and-a-half thick and a solid printed transom and bow. Sections were pinned and bonded together using a Lord Corp. (Cary, NC, US) plural-component urethane adhesive. The assembled pattern was then machined as a single piece on the same Thermwood system, a task that required about 50 hours. The final trimmed pattern weighs approximately 1,364 kg.

After it was printed, trimmed, coated and finished, a fiberglass mold was produced using the printed pattern. Thermwood says this effort clearly demonstrated the feasibility, practicality, economics and advantages of using additive manufacturing in the production of boat tooling.

The Thermwood machine used for the demonstration program has a 10-ft-by-20-ft (3.05m-by-6.1m) worktable, but Thermwood says it also offers larger machines. The machine, as indicated, features both print and trim capability. The head used for this project can print at rates approaching 90 kg/hr when depositing this particular Techmer material.

Additive manufacturing offers the promise of additional advances in marine tooling. Possibilities include printing the hull and deck patterns as single pieces, and allowing a production mold to be taken from the hull and then flipping the pattern over and taking a deck mold from the other side of the same pattern. These concepts promise dramatically lower tooling cost and substantially faster build time.

For large boats and yachts, Thermwood is evaluating the feasibility of printing molds directly, rather than printing a pattern from which the mold is taken. Because of their large size, these tools would be printed and machined in sections and then assembled, even if built with very large LSAM printers. That said, it might be possible to save significant moldmaking time and processing steps by printing integrated channels for air or liquid cooling directly into these large tools.

This initial success and the potential to integrate prvious separate toolmaking process steps indicate that additive manufacturing might find a place in the marine tooling industry's future.

Get a step-by-step look at the Thermwood pattern-printing process on Thermwood's Web site | short.compositesworld.com/Therm3Dblg

AEROSPACE

Single-aisle: Airbus acquires majority stake in Bombardier *C Series*

From left to right: Bombardier board chairman Pierre Beaudoin, Airbus CEO Tom Enders, Bombardier president/CEO Alain Bellemare, and Fabrice Bregier, Airbus COO and president of Airbus Commercial Aircraft. Source | Airbus

An Airbus SE (Toulouse, France) and Bombardier Inc. (Montreal, ON, Canada) partnership announced for the *C Series* aircraft program brings together Airbus' global reach and scale with Bombardier's newest, state-of-the-art jet aircraft family, positioning both partners, they say, to fully unlock the value of the *C Series* platform and create significant new value for customers, suppliers, employees and shareholders.

Under the agreement, signed Oct. 16, Airbus will provide procurement, sales and marketing, and customer support expertise to the C Series Aircraft Limited Partnership (CSALP), the legal entity that manufactures and sells the planes. Airbus will acquire a 50.01% interest in CSALP, while Bombardier and Investissement Québec (IQ) will retain approximately 31% and 19% respectively. CSALP's headquarters and primary assembly line and related functions will remain in Québec, with the support of Airbus' global reach and scale. Airbus' global industrial footprint will expand with the Final

Assembly Line in Canada and additional *C Series* production at Airbus' manufacturing site in Mobile, AL, US. This strengthening of the program and global cooperation will have positive effects on Québec and Canadian aerospace operations.

The partners see the single-aisle market as a key growth driver, representing 70% of the expected global future demand for commercial passenger aircraft. Ranging from 100 to 150 seats, the *C Series* "is highly complementary to Airbus' existing single-aisle aircraft portfolio," which focuses on the higher end of the single-aisle business (150-240 seats). The press materials on the deal also noted that the *C Series* aircraft would benefit from the "world-class sales, marketing and support networks that Airbus brings into the venture" and that Airbus "supply chain expertise is expected to generate significant *C Series* production cost savings."

"This is a win-win for everybody!" says Airbus CEO Tom Enders. "The *C Series*, with its state-of-the-art design and great economics, is a great fit with our existing single-aisle aircraft family and rapidly extends our product offering into a fast-growing market sector. I have no doubt that our partnership with Bombardier will boost sales and the value of this program tremendously. Not only will this partnership secure the *C Series* and its industrial operations in Canada, the UK and China, but we also bring new jobs to the US. Airbus will benefit from strengthening its product portfolio in the high-volume single-aisle market, offering superior value to our airline customers worldwide."

Alain Bellemare, president and CEO of Bombardier Inc., is equally enthusiastic: "We are very pleased to welcome Airbus to the *C Series* program. Airbus is the perfect partner for us, Québec and Canada. Their global scale, strong customer relationships and operational expertise are key ingredients for unleashing the full value of the *C Series*. This partnership should more than double the value of the *C Series* program and ensures our remarkable game-changing aircraft realizes its full potential."

For details of the Airbus/Bombardier partnership arrangement, see *CW's* full coverage online at the *CW* News site | **short.compositesworld.com/AirbusCSer**

See also this month's "*CW*: Past Present & Future" (p. 6) for commentary on the place this deal might hold in the bigger picture of today's international composites marketplace.

AUTOMOTIVE

Volvo performance brand features carbon fiber bodies


Source | Volvo

Automaker Volvo Car Group (Gothenberg, Sweden) made news in summer 2017 when it announced that by 2019, its entire fleet of vehicles would be either hybrid electrics or powered solely by electric motors. As part of that strategy, *Polestar*, the Volvo Car Group's performance brand, has revealed its future as a new standalone electric performance brand.

Polestar has confirmed plans for its first three models, inaugurated its new, purpose-built Polestar Production Centre in Chengdu, China, and previewed the 600-hp *Polestar 1*, the company's first car, which is set to roll off the production line in mid-2019.

A two-door, 2+2 seat grand tourer coupé with an "electric performance hybrid" drivetrain, the *Polestar 1* electric is supported by an internal combustion engine, has a range of 150 km on electric power alone and features a carbon fiber composite body that reduces the car's weight and improves its torsional stiffness by 45%, as well as lowers the car's center of gravity. The *Polestar 1* will be built in the Chengdu production center, which is expected to open sometime in mid-2018.

All future cars in the *Polestar* lineup will have a fully electric powertrain. *Polestar 2* will start production later in 2019 and will be the first battery electric vehicle (BEV) from the Volvo Car Group. It will be a mid-sized BEV, joining the competition around the Tesla *Model 3*, and with consequently higher volumes than *Polestar 1*. The initial phase of the Polestar rollout will be completed by the arrival of a larger SUV-style BEV, the *Polestar 3*.

Volvo Car Group is owned by Geely Automobile Holdings of China (Hangzhou, China), which already makes electric vehicles for the Chinese market. There is strong interest in electric vehicle technology in China as the country seeks ways to reduce life-threatening pollution caused, in part, by internal combustion engines.

■ Low-cost pitch source

The University of Utah (Salt Lake City, UT, US) is one group working on converting ordinary mined coal (rather than coking coal) into pitch that can be spun to form low-cost carbon fiber. This photo shows coal mined in Utah prior to pyrolysis and tar extraction.

Source | *Utah Business Magazine* (10/26/17)

Coal as an avenue to low-cost carbon fibers

An update on efforts to produce pitch-based fibers from low-cost coal.

By Sara Black / Senior Editor

» Making carbon fibers from coal is not new. Since the 1960s, production processes for these pitch-based carbon fibers have been investigated, developed and commercialized by numerous entities, including Mitsubishi Chemical Corp. (Tokyo, Japan) and Nippon Graphite Fiber Corp. (Hyogo, Japan). Mitsubishi's high-performance DIALEAD fiber, for example, is considered by many as essential to the success of many zero-CTE- and stiffness-critical aerospace and space projects.

What *is* new is that, within the past year, several projects have sprung up, with two purposes: 1) find new uses for coal that don't involve power generation, thereby reducing carbon emissions while preserving miners' jobs, and 2) convert this low-cost, carbon-rich precursor into useful, low-cost fibers suitable for *non-aerospace* applications. *CW* talked to two groups about their efforts and their progress to date.

Wyoming coal, a broad consortium

For two centuries, coal has been the source of useful organic chemicals and products, including dyes, explosives, medicines and more — for instance, coal gas was a source of illumination, before the advent of electric lights. Perhaps the most strategically important use of coal, however, has been as a carbon source, called "coke," for steel-making — coal with relatively low ash content and high carbon content, termed metallurgical coal, is the highest and most expensive grade of coal, and is converted to coke by heating it in ovens to drive off water and volatiles prior to its addition to the furnaces used to convert iron ore to steel.

As a carbon fiber precursor, coal is very different from the more widely used polyacrylonitrile (PAN) polymer (see the Side Story titled, "Coal pitch-based fibers vs. PAN fibers" on p. 23). Don Collins, CEO of the Western Research Institute (WRI, Laramie, WY, US), notes that coal contains up to 30% water, comprising a variety of carbon compounds, heavy metals and minerals: "Coal contains hundreds of thousands of complex molecules, encompassing a wide range of molecular weight and solubility." He explains that precursor (liquid) material from coal can be produced by standard pyrolysis, coal gasification (with the gas converted back into liquid), or direct liquefaction using heat, pressure and solvent extraction.

Pitch material is initially isotropic, but can be converted to anisotropic, mesophase pitch — with better-aligned graphitic planar structure — using additional heat treatment and refinement.

The existing commercial coal pitch-based fibers are made from the high-end, metallurgical coking coal, with fewer impurities than typical coals, to produce their high-property fibers, using proprietary heating and refining steps, adds Charlie Atkins, director of development at Wyoming iPark (Sheridan, WY, US). Atkins' firm is working with WRI, mining company Ramaco Carbon LLC (Sheridan, WY, US) and a group of firms within the composites industry as part of a three-year, US$6 million US Department of Energy (DoE) cost-sharing project (announced July 2017) under the Integrated Computation Materials Engineering (ICME) umbrella to develop low-cost carbon fiber from a variety of low-cost feedstocks and precursors, including typical, *non-coking* Wyoming coal, with the goal to make carbon fiber with less energy at a lower cost. Atkins has a long history with pitch-based fibers, given that his father Orin Atkins once headed Ashland Oil, which did considerable work on developing pitch products, based on petroleum, in the 1970s.

"We're coming from a much different perspective, and are focused on vertical integration from very low-cost, non-coking coal to useful products. Our principal goal is coal to carbon fiber, followed by development of useful resins as well as carbon forms to support 3D printing," explains Atkins, adding that pitch is not the only precursor under consideration during the project; team member Southern Research (Birmingham, AL, US) is investigating sugar bio-mass as a bio-based alternative to polyacrylonitrile (PAN) precursor.

High-purity metallurgical coking coal can cost US$200/ton, but the Ramaco coal feedstock is priced closer to US$10/ton. Collins explains that WRI has already developed a trademarked pilot process it calls WRITE-Coal, originally developed under a clean coal project to reduce mercury emissions at power plants. With its multi-stage heating process, he says, the water in the coal can be recovered for beneficial use. Then, mercury, arsenic and selenium, all of which vaporize at a higher temperature (~176°C) also can be recovered. Finally, heavy metals are released and captured as temperatures reach 315°C. What is left are the tars and pitch (e.g., aromatic and asphaltene fractions) that liquefy with continued heating. Collins says that mesophase precursor (see Side Story) is the primary goal, although the group will work with the tars and oils produced: "With filtering and beneficiation steps, we can achieve a variety of precursors for experimentation. It will not be 100% mesophase, and we'll study blends of isotropic and mesophase pitch formulations," says Collins, who recently presented two papers on coal »

SIDE STORY

Coal pitch-based fibers vs. PAN fibers

Pitch-based carbon fibers differ from polyacrylonitrile (PAN)-based carbon fibers in terms of precursor, processing and final fiber properties. Pitch precursor is derived from a host of polyaromatic hydrocarbons stemming from coal and petroleum, while PAN precursor is based on acrylic polymer chemistry derived from petroleum. PAN fiber processing steps include polymerization, fiber spinning, washing, stretching to orient the polymer chains, oxidative stabilization and two-stage carbonization (low and high temperature).

Pitch-based fiber from coal (and petroleum) first involves multi-step processing to produce a usable heavy oil, with further refinement of the resulting heavy oil to produce a spinnable pitch material. This is followed by spinning of "green" fibers, oxidative stabilization and carbonization, with the option for even higher temperature graphitization. The pitch is initially isotropic, which can be used to produce standard-grade (non-aerospace) fibers. Further heat treatment of the pitch creates a mesophase, or anisotropic form of pitch, which can orient along the fiber axis and graphitize to form high-modulus, high thermal conductivity continuous fibers, which have a modulus up to 20 times greater than isotropic fibers.

PAN carbon fiber starts with a higher initial precursor cost of US$4-$5/lb [US$1.82-$2.27/kg] for polyacrylonitrile precursor. This compares to an estimated cost of $1.50/lb [US$0.68/kg] for mesophase pitch precursor for pitch-based carbon fibers, says Chris Boyer, COO and VP of Advanced Carbon Products LLC (Hitchins, KY, US).

A key difference between PAN and pitch fibers is carbon yield, says industry expert Chris Levan, president of Carbon Fiber Solutions (Alpharetta, GA, US) and a consultant to ORNL: "White" PAN fiber (before carbonization) contains about 50% (by weight) carbon, while pitch fiber (before carbonization) yields about 85% (by weight) carbon. That means the ultimate finished carbon fiber cost is lower using pitch, given roughly comparable performance properties. Pitch fiber processing, typically melt-spinning, is faster and less complex, overall, than PAN processing, and can be performed at a higher rate, resulting in greater throughput and reduced capital cost. Pitch processing produces fewer greenhouse gases than PAN, resulting in a smaller carbon footprint, adds Boyer.

In terms of general fiber properties, mesophase pitch-based structural carbon fibers have high modulus (stiffness) and moderate strength. PAN-based fibers have moderate modulus and high strength (higher strain-to-failure) and toughness (area under the stress-strain curve) and higher compressive strength. These properties are related to their fundamental crystal structure, and differences between graphitized mesophase pitch fibers and intermediate-modulus PAN fibers, explains Dr. Matthew Weisenberger, associate director of the Center for Applied Energy Research (CAER) Carbon Materials Technologies Group at the University of Kentucky (Lexington, KY, US): "These differences have historically driven the structural carbon fiber market towards PAN-based fiber — something like 90% of the CF market is PAN-based. But as new applications arise that demand lightweight, high-stiffness parts, pitch-based carbon fiber could begin to nibble away at PAN's market share, but only if it can bring a cost advantage. I think that efficient coal-to-materials [carbon fiber and other products] is at the heart of the economics."

According to Boyer, "Scaling up PAN-based fiber production to meet the potential automotive industry demand would require a much longer time and greater costs than scaling up pitch production, in terms of obtaining the basic raw materials. The plants that produce propylene and ammonia, the basic constituents of PAN, currently have no excess capacity, but the pitch feedstocks are made today and would require very little additional investment."

CF from Utah coal

The University of Kentucky (Lexington, KY, US), partnered with the University of Utah, is spinning and testing pitch-based fibers, shown here, originating from Utah coal. The program is under the direction of Dr. Matthew Weisenberger, associate director of the Center for Applied Energy Research (CAER) Carbon Materials Technologies Group.

Source | University of Kentucky

chemistry at the 2017 Pittsburgh Coal Conference (held Sept. 5-8, in Pittsburgh, PA, US).

Project stakeholder Oak Ridge National Laboratory (ORNL, Oak Ridge, TN, US) will spin precursor formulations submitted by Ramaco/WRI team members into fibers. Advanced Carbon Products LLC (ACP, Hitchins, KY, US), for one (see Learn More), has a pilot-scale continuous process for making mesophase pitch fiber precursor, reportedly for as little as US$1.50/lb, and, Atkins confirms, will supply its samples to ORNL to fabricate and assess fiber quality and performance. Carbonization will occur at ORNL's Carbon Fiber Technology Center (CFTC). Fiat Chrysler (London, UK), General Motors (Detroit, MI, US), Hexcel (Stamford, CT, US), Solvay Composite Materials (Alpharetta, GA, US), Harper International (Buffalo, NY, US) and Autodesk (San Rafael, CA, US), acting in an advisory capacity, will provide guidance to the project team by addressing industry questions and needs. Autodesk, which acquired the University of Wyoming software spinoff Firehole Composites several years ago, and the University of Wyoming Mechanical Engineering Dept. (Laramie, WY, US), will be involved in advancing mechanical analysis and modeling software capabilities to provide industry with state-of-the-art design tools to facilitate quick application of project carbon fibers for automotive applications.

An important goal of the ICME project is to go beyond simply proving that low-cost coal can be an effective precursor, says Collins: "We aim to study the chemistry of these pitch formulations and determine which are best-suited for making carbon fibers of differing properties. We want to advance the scientific understanding of the molecular structure of these compounds, and develop a 'knowledge portfolio' or catalog of different fiber properties with the Grossman Group at the Massachusetts Institute of Technology [MIT, Cambridge, MA, US]."

In other words, certain combinations of pitch constituents will produce greater stiffness, while others might have a lower tensile modulus with higher strength. Steel and other metals, for which standard forms have been developed, with known properties, are now available from a catalog. Collins believes the same should be true for carbon fibers. He adds, "Our goal is to be able to vary the chemistry to get custom carbon fiber properties useful to the automotive industry."

For now, the entities that are part of the grant project are using a reactor to heat the coal, but Atkins says an autoclave can accomplish similar results. He notes, "We have a good shot at coming up with a low-cost carbon fiber over the course of this project."

ACP's chief operating officer and VP of marketing and sales Chris Boyer adds, "Pitch fibers with adequate properties for

ORNL ready for a spin

Oak Ridge National Laboratory's (ORNL) Carbon Fiber Technology Facility (CFTF) will spin pitch-based fibers derived from Wyoming coal, under a second project, working together with Wyoming's Western Research Institute (WRI), Wyoming iPark, and Ramaco Carbon LLC, and a team of partners, including Advanced Carbon Products LLC (ACP, Hitchins, KY, US). ACP already makes low-cost mesophase pitch fiber precursor.

Source | ORNL

automotive applications — 250 to 300 Ksi tensile strength and 25 to 50 Msi modulus — can potentially be produced that can meet the automotive target price of $5/lb."

Utah coal as pitch

In another effort, engineers from the University of Utah (Salt Lake City, UT, US) launched, in October 2016, a US$1.6 million, three-year project to research "cost-effective, carbon-friendly methods" for converting coal pitch into carbon fibers, and to evaluate the process's market potential for revitalizing Utah's coal communities, which have been threatened by a nationwide decline in coal extraction. Headed by chemical engineering professor Eric Eddings, the project's funding benefits from a POWER grant from the US Economic Development Admin. (EDA, Washington, DC, US) and additional assistance from the Utah Advanced Materials and Manufacturing Initiative (UAMMI, Salt Lake City, UT, US).

LEARN MORE

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

Read more *CW* editorial about research into carbon fiber derived from coal-based precursors:

"Coming to carbon fiber: Low-cost mesophase pitch precursor" | short.compositesworld.com/CFMesoPtch

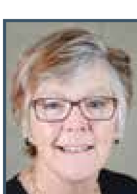
"Researchers working on turning coal into carbon fiber" | short.compositesworld.com/Coal2CF

"We've now got the reactors built and in place," Eddings reports. "We've been producing pitch over the past several months, at a bench-top scale." He explains the project focus is to explore different operating conditions and their effects on the produced pitch. Fibers will be spun and carbonized at the University of Kentucky (Lexington, KY, US) by a group of researchers under the direction of Dr. Matthew Weisenberger, associate director of the Center for Applied Energy Research (CAER) Carbon Materials Technologies Group. There, different operating conditions will be tested as "green" fibers are spun (prior to air stabilization and carbonization), as well as after carbonization, to determine the optimal fiber production parameters. The initial carbon fibers derived from Utah coal have very recently been produced at CAER.

What is the "ideal" pitch material from low-cost Utah coal? Says Eddings, "It really depends on the application needs. Aerospace-grade fiber obviously has been perfected, but is costly due to the need to meet modulus and strength quality-assurance requirements. For automotive applications, it will depend on the part being considered. We hope to be able to design or 'right-size' a fiber for a specific application." For non-aerospace uses, pitch refinement steps can be reduced and simplified. Eddings says the group is investigating mesophase and isotropic pitch (for how these differ, see the Side Story), to identify which is most suitable for particular applications. Less-costly isotropic pitch might suffice in some cases.

Although exact details weren't revealed because the process may be patentable, Eddings says the coal is pyrolized (without air), with the resulting liquids separated to capture the heaviest molecular weight tars, then refined. This is followed by more heating to drive off the lighter constituents, which, he says, are captured for possible reuse, as is the residual char, which may have value as coke or other carbon-based materials: "First we'll produce fibers, then optimize the process based on the feedstock."

"Our main goal is to get to a fiber that is less expensive to produce than PAN fiber, and with the right combination of tensile modulus and strength," concludes Eddings. "We have many ideas for secondary recovery of related products to improve the project's economics." He adds that the coal-mining community is desperate for a new direction, and that economical alternative uses for the product should be investigated and developed. CW



ABOUT THE AUTHOR

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The calm after the blast shock wave

This developmental reinforced elastomeric film, seen here still suspended and retaining its integrity, post-blast, during field testing, is designed to be attached to the interior of concrete masonry walls and provide blast-debris protection to occupants. Capable of stopping flying stone, wood debris, and falling cinder blocks (as in the photo), the flexible composite shield is easily transportable and can be installed at remote locations. The prospective product, when commercialized, will offer an appealing alternative, its designers claim, to more costly and cumbersome building hardening materials, such as steel or concrete.

Source | ERDC

Armor update: Reinforced elastomeric composite blast barrier

A new, flexible, lightweight, portable debris shield holds promise for protecting building occupants in military zones.

By Michael LeGault / Contributing Writer

» A unique, fiber-reinforced elastomer holds promise as a retrofittable, blast-resistant "wallpaper" that could help mitigate the hazard of flying debris when a non-loadbearing, concrete masonry wall is subjected to a pressure wave from a high-explosive event. Developed by the US Army Engineer Research & Development Center (ERDC, Vicksburg, MS, US), the blast protection system has received several awards, including a Top 100 Innovation Award from *Popular Science* magazine.

Development and testing are ongoing, but when the product is fully qualified, a fabricator plans to launch a commercial line and market it under the tradename X-FLEX Composite Blast Protection System. In its basic configuration, the system consists of an extruded urethane elastomeric film or membrane attached to or embedded in an aramid fiber-reinforced mesh.

In general terms, the innovation is intended to provide an alternative to more costly and cumbersome conventional building retrofit techniques for 'hardening' structural components against blasts, such as adding concrete or steel. Instead, the wall retrofit now under development is readily transportable and can be installed quickly and easily at remote locations without the need for specialized equipment or training. More importantly, the research and experiments conducted at the ERDC have demonstrated the reinforced wall retrofit system's effectiveness in mitigating debris hazards that result from blast events by preventing debris fragments from entering the interior areas occupied by people. The system, however, is not designed to stop shrapnel emanating from the explosive ordnance itself.

A spokesperson at the East Coast fabricator involved in the project says the ERDC solicited the company's help in developing the product because of its expertise in manufacturing layered film materials. The company has developed an extrusion process to manufacture a number of prototype versions of the reinforced elastomer wall retrofit used in the battery of tests conducted by the ERDC and Army Corps of Engineers.

With a near-term objective of demonstrating and proving the capability of a portable wall retrofit system, ERDC researchers decided to design, build and test the wall retrofit using a reinforcement with a well-known, qualified ballistic history within the Army, i.e., Kevlar, supplied by DuPont Protection Solutions (Richmond, VA, US).

To commence the project, ERDC contracted the Georgia Institute of Technology (Savannah, GA, US) to conduct tensile tests on reinforced and unreinforced coupons made with a variety of resins, some of which included spray-on polyureas, trowel-applied thermosets, polyurethane and thermoplastic films. Additionally, the aramid-reinforced coupons were made using a variety of mesh orientations and patterns. The coupon testing enabled researchers to pre-screen and pare down numerous resin and reinforcement combinations to a promising handful.

A critical piece of project equipment has been the ERDC's Blast Load Simulator (BLS), which has enabled researchers to assess not only different materials, but also various ways of optimizing the manner in which the composite mesh is attached to the interior of a wall. The facility currently operates two of the devices, a full-scale BLS, designed to simulate explosions on target walls up to 8 ft by 8 ft (2.4m by 2.4m), and a sub-scale BLS, which can accommodate targets up to 54 inches by 71 inches (1,371 by 1,803 mm). Because the full-scale BLS became operational shortly before testing for the X-FLEX development program was completed, all the testing for this project was done using the sub-scale BLS and then validated with high-explosive field tests.

The simulator's three main components are a compressed air driver, an expansion cone with transition rings, and a target vessel. Pressure is created by the release of compressed gas from the cylindrical driver. Shock waves are generated at the front of the expanding compressed air as it travels through the expansion cone to the specimen mounted on the target vessel, with a potential maximum load of up to 20,000 lb at peak reflected pressures.

The BLS is designed to conduct two types of experiments. The first, a diffraction/engulfment experiment, documents the effect of the pressure wave as it passes by the target — that is, it simulates the effects of an *indirect* hit from an explosive device. The second, and the one applicable in this project, a fully reflected target experiment, evaluates the structural response of walls, windows, concrete slabs and composite panels, as the target is subjected to the fully reflected pressure wave on the target surface.

Carol Johnson, a research civil engineer at ERDC, says numerous design-of-experiment-type tests, entailing use of a Blast Load Simulator to create an explosive-like pressure wave impingement on a concrete cinder-block wall retrofitted with the X-FLEX barrier, were used to evaluate various resin/reinforcement combinations and constructions. One of the best-performing designs, she reports, comprised a polyurethane elastomer matrix extruded over a ±45° aramid mesh, impregnating the fibers and filling the voids between the fibers in the mesh structure to form a solid sheet. A similar construction, albeit one in which the polymer, already in sheet form, is laminated onto the mesh, also was tested. However, the extruded version outperformed it. The Kevlar fibers were purchased already woven together in the desired orientation.

In the project's initial stage, ERDC employed a manufacturer to sandwich the fibers between two layers of elastomeric film. The films were applied on either side of the fabric layer through a »

Post-test protection benefit validated

ERDC conducted a battery of experiments, using its sub-scale Blast Load Simulator in concert with high-explosive field tests to assess and validate the performance of various designs of the elastomeric reinforced wall retrofit structures. Here, in a field test setup, a concrete cinderblock wall has its interior wall retrofitted with an aramid-reinforced elastomeric blast-protection film (top). After explosive device detonation, the wall is destroyed, but the protective film, anchored to the floor and ceiling with steel studs and adhesive, remains intact, protecting its data-collecting dummy occupant (bottom photo). Source | ERDC lamination process. In the later stages, when fiber type and orientation, and the elastomer, had been pared down to a few promising materials, this lamination technique was transitioned to a system similar to a sheet extrusion process, developed by the fabricator that will commercialize the product, in which the roll of Kevlar fabric and elastomer are extruded through a tool or die that facilitates complete encapsulation of the fibers by the elastomer.

The ERDC team also tested three ways of attaching the composite mesh retrofit to the wall and floor substrate:

1) Mechanical attachment, by a variety of means, to the floor and roof immediately adjacent to the wall.
2) A combination of mechanical attachment and a rubber or acrylic pressure-sensitive adhesive applied to the wall-facing side of the extruded fiber-reinforced elastomeric film. Upon installation, a backing paper is removed and the reinforced film is bonded directly to the wall substrate. Top and bottom mechanical attachments also were secured in place by an epoxy or elastomeric adhesive applied with a roller or grooved trowel. The elastomeric material thickness can be 0.01-0.25 inch (0.25-6.35 mm).
3) Item 2 above, with the wall and top and bottom attachment areas prepared with a primer. When the primer becomes tacky, an adhesive is applied to the top and bottom attachment areas. A rubber roller is used to apply pressure to the reinforced elastomeric wall retrofit to ensure integral contact and adhesion to the entire wall surface. Both the pressure-sensitive adhesive and attachment area adhesive react with the primer to form a chemical bond.

Of the three methods, the third performed best in tests. Mechanical attachment to the floor and ceiling frame comprises either a steel plate or steel stud member secured in place with adhesive and anchor bolts. Holes are drilled into the floor spaced 3-4 inches (76-102 mm) apart, and each hole is fitted with a sleeve for the anchor bolts. The adhesive on the top and bottom supports prevents the reinforced elastomer from slipping between the anchor bolts during a blast.

Johnson says the wall retrofit technology is best viewed not as a single system, but rather as a suite of materials (reinforcements and resins) that can be tailored to deliver various degrees of protection, through modifications to materials, component configurations and geometry, which in turn depend on the level of the anticipated threat and the funding available to pay for it.

Possible resins include polyurethane, polyethylene, polypropylene and thermoplastic blends. Similarly, in addition to aramid, the reinforcement mesh could, theoretically, be made from fiberglass, carbon, polypropylene, nylon or a hybrid fabric. By mixing and matching this matrix of reinforcements and resins, as well as altering physical design parameters, it is possible to manufacture a reinforced elastomeric wall retrofit with a yield strength of the embedded reinforcement of 100-800 lb (45.4-363 kg) per lineal inch. “There is definitely an aspect of tunability to the product to accommodate the threat level required to protect personnel against,” says Johnson.

Although there are no immediate plans to launch X-FLEX commercially, the fabricator’s spokesperson says it is a product to which it remains committed and would like to sell it to the military and the public. “It is a system that can certainly save lives, and we have received interest in it from all over the world.”

As a cost-effective and user-friendly means to afford protection and save lives against a variety of threats, it seems safe to assume it is not a matter of if but when the composite blast mitigation system is installed in real-world applications. CW

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Read this article online |
short.compositesworld.com/X-FLEX

Read more on this subject in the following:

“Antiballistics: Better defense, less expense” |
short.compositesworld.com/AntiBal

“Antiballistic composites: Course corrections” |
short.compositesworld.com/AntiBalCor

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Ultimate goal: Fully automated, defect-free

Siemens' almost fully automated factory in Amberg, Germany, makes its Simatic programmable logic controls (PLCs) with virtually no defective parts, and serves as a demonstration of smart manufacturing. Source | Siemens

Composites and Industry 4.0: Where are we?

As the tide of the Fourth Industrial Revolution rolls in, how will composites manufacturers ride the wave?

By Sara Black / Senior Editor

» About 250 years ago, steam-powered machines began to displace manual labor in the Industrial Revolution. A Second Industrial Revolution, spurred mainly by electrical power, enabled the assembly lines and factory workflow. Think Henry Ford's Model T. In the 1960s, computers spawned a Third Industrial Revolution, birthing digital design software and robotics. Key word? *Automation*.

Teaching machines to "think"

Today, there's a *Fourth* Industrial Revolution. In it, integrated, intelligent cyber-physical systems — built around sensor-equipped manufacturing machines — are connected to the Industrial Internet of Things (IIoT) and are, therefore, able to *autonomously* manufacture digitally designed products, maintain their quality and perform activities along the entire value chain. Deloitte University Press (Sniderman, Mahto and Cotteleer, Feb. 22, 2016) calls it "the marriage of advanced manufacturing techniques with information technology, data and analytics." Tech guru Chandrakant Patel of HP Labs (Palo Alto, CA, US) has been quoted as saying, "We are operating at the intersection of machine learning, data management and domain knowledge."

There are several ways to refer to this trend, or aspects of it: Europeans refer to it as Industry (or Industrie) 4.0 (see the Side Story titled "Industry 4.0: A rose by any other name …." on p. 35), but it is also variously known as the IIoT, digital enterprise and digital thread. And in the US, the nonprofit initiative Smart Manufacturing Leadership Coalition (SMLC, Los Angeles, CA, US) calls it smart manufacturing. Industry 4.0 and smart manufacturing are used interchangeably here.

Industry 4.0 isn't a "coming trend" or theoretical concept. It's here, it's real and is already having an impact in factories around the globe. General Electric (GE, Boston, MA, US), for example, calls its approach to it "Brilliant Manufacturing": Its product design, engineering and manufacturing functions, its supply chain, logistics and distribution arms, its consumer buying trends data management and even its repair services are all interconnected in *one globally scalable system*.

And, Industry 4.0 *is* trending in the composites industry, but more so in Europe, particularly in plants that supply the aerospace and automotive industry (see Learn More).

Many in the composites industry, however, have been slow to get on board. One reason is that composites are more challenging than other industries in terms of data collection and management. "There are a lot of inherent complexities in composites fabrication," says Dale Brosius, chief commercialization officer for the Institute for Advanced Composites Manufacturing Innovation (IACMI, Knoxville, TN, US). The wide range and potential combinations of fibers and thermoset and thermoplastic raw materials; multiple tools and molds; energy-intensive autoclaves and ovens; and the extensive documentation requirements in some sectors complicate every aspect of design and manufacture. "But that means the composites industry has *more to gain* from smart manufacturing deployment than many other 'simpler' industries," says Brosius (see Learn More).

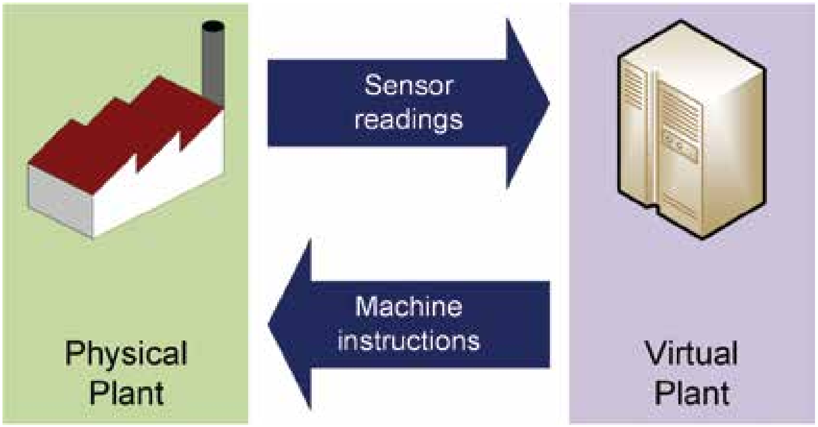
Most importantly, Industry 4.0 means a commitment to software-based business management. Dr. Leslie Cohen, senior VP of new business development and strategic technology at HITCO Carbon Composites (Gardena, CA, US), observes, "Smart manufacturing means the end of 'analog' processes, using paper, paper clips and markers. Analog processes do not scale well, if you want to grow your business."

The good news is, "going paperless" can be readily accomplished. "You can achieve full return on investment [ROI] in 3 to 6 months," claims Avner Ben-Bassat, CEO of IIoT software »

Seeing in real-time

A ZyynTek sensor from EmergenTek (South Jordan, UT, US) is used to monitor prepreg material management for customer Composite Solutions. The photo below shows the sensor in place on the outer wall of a freezer.

Source (both photos) | EmergenTek



Promoting an actual/virtual conversation

This simple diagram developed by ATS Applied Tech Systems (Nuneaton, Warwickshire, UK) shows the relationship between the actual factory floor and the "digital twin," or virtual plant, that sensor-collected data enables. Source | ATS Applied Tech Systems Ltd.

and technology firm Plataine Technologies Ltd. (Waltham, MA, US and Petach Tikva, Israel). Most importantly, it will soon be a necessity. “Look, our world is going to change significantly driven by this technology and you can’t sit around and do nothing. You must digitize or die!”

Boundary-less design/manufacturing

The overarching idea of smart manufacturing is to eliminate the boundary between the design world and the manufacturing world, and integrate the two throughout the entire product lifecycle, says John O’Connor, the director of product and market strategy at Siemens PLM Software (Plano, TX, US). “Integrated design and production has been ongoing for a while,” he says. “The longer goal on the horizon is a complete cyber-physical factory, where the product design data is so complete that the manufacturing is done with totally integrated automation, which can recognize and fix any errors in real time. We’re still not to that point yet.”

“Three enabling technologies are powering Industry 4.0,” Ben-Bassat points out. “First, the software tools, algorithms and artificial intelligence programs have matured, and second, the IIoT sensors cost less and are much more robust. Third, the ‘cloud’ affords massive data storage and computing power for data analysis. It’s a perfect storm of opportunity.”

O’Connor goes on: “To make total integration happen, a company needs a digital enterprise platform software program that allows digital simulation and a common data model or language that eventually can accommodate manufacturing workflow as well.” Siemens, for example, offers product lifecycle management (PLM) and manufacturing operations management (MOM) software portfolios to customers, which aggregates

SIDE STORY

Data, process flow and the Theory of Constraints

No stranger to manufacturing, plastics, composites or aerospace, Royal Engineered Composites (Minden, NE, US) opened its doors as a provider of structural plastics manufacturing services in 1949. Eventually, Royal converted to molding structural composites, providing radomes, secondary structure, fairings, access doors and other parts for Boeing, Bell Helicopter, Middle River Aircraft Systems and more.

A few years ago, Royal did something very Industry 4.0-like: It started collecting data — specifically, data on its scrap rates. In short, says operations excellence operative John Loucks, the company was experiencing high rates of prepreg outlife expiration. The company did a few things. First, it started generating monthly expiration reports and directed manufacturing personnel to use about-to-expire prepreg before newer prepreg.

Second, weekly assessments were done to compare the volume of scheduled prepreg consumption against the volume of about-to-expire prepreg on hand and tried to make sure that about-to-expire prepreg was consumed as much as possible.

Third, says Loucks, the company started assigning composite materials a financial risk value based on their states of cure. That is, cured material (accounting for labor and overhead) was assigned a higher value relative to the value of uncured material. Royal won’t reveal the value of either, or the difference, except to say that cured composites have a “significantly greater” value associated with them. In short, in terms of potential for financial loss, says Loucks, “scrapped material is bad. Cured scrapped material is really bad.”

This led, subsequently, to a series of related analyses that attempted to do two things: Identify manufacturing choke points, and then determine the dollar value of each choke. This helped the company then find root causes of choking, the cost of that choke and the best ways to optimize the choke and minimize the cost. Take, for instance, the autoclave: “It’s not rocket science to say that the autoclave is a critical resource in a composites shop,” quips Loucks. However, good use of the autoclave depends on efficient bagging and loading of parts. And those functions depend on efficient kitting and layup, which depend on efficient nesting and cutting and, in turn, on nesting software that has the sophistication and flexibility to allow cutting of multiple kits in a single pass on the cutting table.

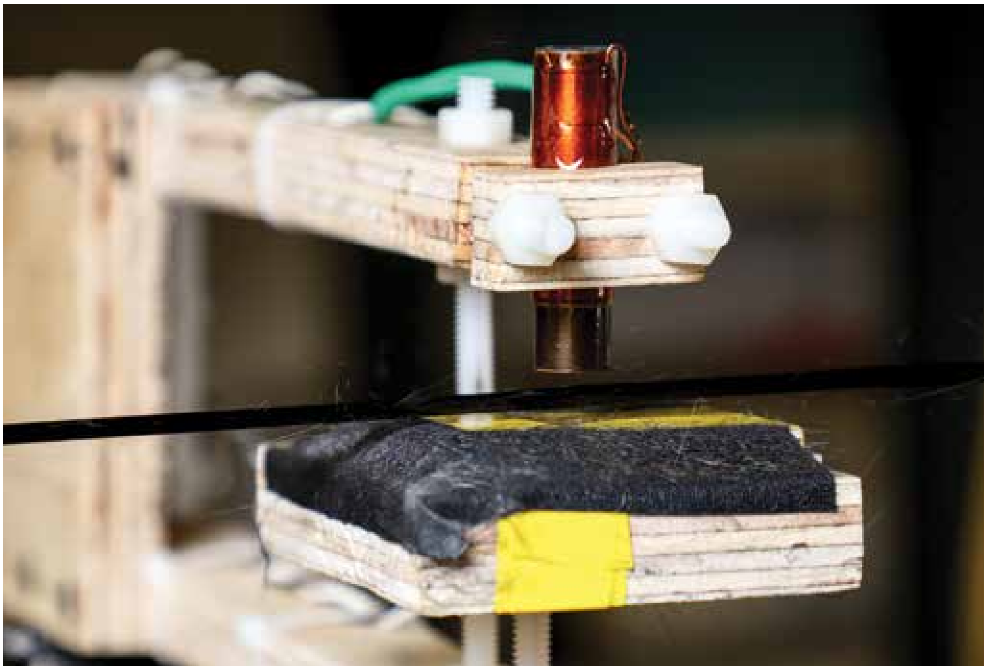
Analysis of these interdependent, cascading process steps, says Loucks, led Royal eventually to the Theory of Constraints, which uses lean manufacturing principles to build a value stream map, on which manufacturing flow and cycle time take priority over all other manufacturing variables — including unit cost. “Basically,” says Mike Borzekofski, materials manager, “we are driving everything down to the root cause, finding the hidden cause of impediments to flow.” And when such a cause is found, steps are taken to remove or minimize the impediment, through better use of material, labor, consumables and/or procedures. Visual tools — enterprise resource planning (ERP), real-time schedules, shadow boards — throughout the facility help make sure that all employees see the status of workflow. “We make sure people have clear signals about what they’re supposed to do,” Borzekofski says.

Other tools/processes include daily scrap reviews with operators to identify issues, Scrap TV to show operators photos of scrapped parts and the cause of the defect and a scrap table with labeled parts that operators are encouraged to see and handle. But Borzekofski is careful to emphasize that it’s not about finger-pointing. “We don’t identify the operator responsible [for the scrap],” he points out. “We identify the cause and the solution. The culture is ‘let’s fix this.’ Honest mistakes are honest mistakes.” Royal wants to encourage employees to step forward, he notes, without feeling like they will be blamed.

The effort, says Loucks, has yielded a substantial return on investment: Scrap caused by prepreg outlife problems has been reduced by 30%; on-time delivery to customers has been increased from 80% to 98%; Royal’s ability to respond quickly to customer needs has been increased substantially; minimum buy requirements of customers has been reduced; and 80% of work orders are completed in less than 16 days (ultimate goal is <10 days).

“That emphasis on flow is what helps us control our WIP [work in progress],” says Loucks. “By de-emphasizing unit cost and looking at the system cost, we avoid fixing a process that is not impacting flow. And that efficiency creates value.”

— Jeff Sloan



Developmental smart manufacturing sensor system

This hand-built prototype of a noncontact measurement system is shown monitoring carbon fiber properties during fiber production at Oak Ridge National Laboratory's (ORNL, Oak Ridge, TN, US) Carbon Fiber Technology Facility. The inline measurements are used to adjust machine actions, as part of a smart manufacturing initiative.

Source | Oak Ridge National Laboratory / US Department of Energy

multiple separate software applications (e.g., Fibersim, NX Nastran, Simatic), which enable not only part design, but also the digitization of scheduling, manufacturing execution, quality management and manufacturing intelligence (see the Side Story titled "Industry 4.0: Sources for software and services," p. 36). Through its Simatic IT manufacturing software systems and Sinumerik sensors, Siemens can offer manufacturers a complete Industry 4.0 enterprise platform, and many other sources of smart sensors are available.

But, before *any* manufacturing takes place, he stresses, "*Composite* materials and parts require specialized development processes because of their complexity, to fit into this Industry 4.0 environment." That means more analysis and cross-disciplinary interaction during design, more virtual testing and more verification. And, in addition to the full digital *part design*, the manufacturing process also must be fully modeled and understood as well, before turning on a single machine. This manufacturing digital model is termed the *digital twin*.

The digital twin is the 3D model and associated data that simulates the entire manufacturing process.

The digital, or virtual, twin is a three-dimensional model plus the associated and extremely elaborate product data structure created to simulate the entire manufacturing process. It's a virtual representation that "fully describes" everything involved with making the part or component — i.e., a digital replica of the part and all the physical assets necessary for its manufacture. Says O'Connor: "The digital twin defines exactly how those details of the part design — ply layup, tolerances, orientations — will be executed by manufacturing machines, down to the smallest details." Some digital twin models are so complete that virtual reality goggles allow workers to interface with model elements.

Digital design of the physical workflow

The digital twin establishes beforehand the exact workflow that will occur on the factory floor. Once manufacturing begins, actual, physical production steps are verified by the smart sensors located on machines and other assets along the way. The sensors collect and send data to a cloud-based repository or database, where data analysis compares the actual factory to the digital twin, confirming that the part is being produced within the modeled norms. "The digital twin model software captures all of the minor differences or deviations between the actual part from the designed part, and runs analytics on that data and the deviations," says Ben-Bassat. "That's how we can perform predictive maintenance, for example, because we now know that a part might have a slight flaw, and need repair or replacement sooner."

"We can verify immediately if all fiber tows are present, for example, and if the process is drifting, for instance, in the degree of cure," says Brosius. The management control software then makes needed machine changes to correct the drift, because the actual physical factory floor is constantly compared to the digital twin standard. Adds O'Connor, "Ultimately, the collected data provides traceability to confirm the part is correct, and built as designed and as simulated. The digital twin supports the real-world process." And that process has the potential to significantly increase manufacturing efficiency, improve part quality, reduce scrap and cut the cost of composite parts.

Notably, Siemens has operated, since 1989, an almost fully automated factory in Amberg, Germany, which makes 12 million Simatic programmable logic controls (PLCs) per year. Production »

SIDE STORY

Industry 4.0: Acronyms and expanded definitions

The Fourth Industrial Revolution and the phenomenon of Industry 4.0 has spawned a number of related acronyms, many connected to the digital tools used in the development of the digital twin that mirrors the physical workflow in the production line envisioned in the 4.0 future. What follows are key acronyms, brief definitions and, in several cases, Web sites to visit that can offer more in-depth insight into the genesis and use of the terms:

CAPP = computer automated process planning; the use of computer technology to aid in the process planning of a part or product, in manufacturing (Wikipedia.com).

CPS = cyber-physical systems; those that integrate software-based computation, networking, and physical processes (cyberphysicalsystems.org).

DDM = data-driven manufacturing; a manufacturing process based on facts, not guesses, wishes, theories or opinions (*Modern Machine Shop* magazine).

ERP = Enterprise resource planning; business process management software that allows an organization to use a system of integrated applications to manage the business and automate many back-office functions (Webopedia.com).

HPC = high-performance computing; the practice of aggregating computing power in a way that delivers much higher performance than one could get out of a typical desktop computer or workstation in order to solve large problems in science, engineering, or business (insidehpc.com).

IIoT = Industrial Internet of Things; the use of internet of things (IoT) technology in manufacturing (Accenture.com/us-en/labs-insight-industrial-internet-of-things).

IO-Link = interoperability link technology; an open-standard protocol for integrating sensors for data collection and control (io-link.com).

IVL = information value loop; how information creates value, how to increase that value, and positioning an organization to capture value (stephensonstrategies.com/deloittes-iot-information-value-loop-critical-attitudinal-shift/).

MES = manufacturing execution system; a control system for managing and monitoring work-in-process on a factory floor (searcherp.techtarget.com/definition/manufacturing-execution-system-MES).

MOM = manufacturing operations management; a methodology for viewing an end-to-end manufacturing process, with a view to optimizing efficiency (Wikipedia.com).

MRP = material requirements planning; a planning and control system for inventory, production, and scheduling (smartsheet.com/guide-to-material-requirements-planning).

OEE = overall equipment effectiveness; a method of measuring manufacturing productivity (oee.com).

PLM = product lifecycle management; the creation and central management of all product data and the technology used to access this information and knowledge (product-lifecycle-management.info).

PLC = programmable logic controller; an industrial digital computer which has been "ruggedized" and otherwise adapted for the control of manufacturing processes, such as assembly lines or robotic devices (Wikipedia.com).

RFID = radio frequency identification; a generic term for technologies that use radio waves to automatically identify people or objects (rfidjournal.com).

quality is reportedly 99.99885% — virtually no defective parts (see photo, p. 30, and see Learn More). Most composites companies may not have the means nor the need to set up a completely automated facility, but anyone can adopt and introduce elements or pieces of smart manufacturing technology to improve production and reduce defects. Plataine's Ben-Bassat says, "Manufacturing can really benefit from the Industrial Internet of Things. It's a matter of determining how one can get the most value from it."

Plataine is well known for its artificial intelligence (AI)-based optimization software and managed solutions for aerospace composites manufacturers (see Learn More). With strong domain knowledge in composites, Ben-Bassat is aware of the time-consuming "bottleneck" tasks, such as manual tracking of composite prepreg material, in and out of the freezer, and the "travelers" or paper sheets that are required for auditing. He recommends starting there.

Although client projects are proprietary, *CW* has seen, first hand, how Composites Technology Center (CTC), a subsidiary of Airbus Operations GmbH (Stade, Germany, see Learn More), is employing Plataine's system. At CTC, incoming materials received, including prepreg and dry fiber rolls, are identified with an attached sensor. The material information is input into a software program, which relates supplier name, batch number, type of material, remaining shelf life, etc., to that sensor, which then communicates, via radio frequency or Bluetooth low energy (RFID or BLE), with the program the exact time it has changed location, or experienced deviation in another monitored parameter. Sensor cost is minimal (as little as US$1 each), depending on size and what it detects and transmits.

The data transmitted by the prepreg roll sensors and their out-time movements are analyzed by Plataine's artificial intelligence software. Algorithms then direct workers via screens or tablets to the rolls to be used each day, on each shift, to ensure oldest material is used first, and that out-time is not exceeded. The company also can assist with nesting and kitting programs to optimize material usage. Says one industry insider familiar with Plataine's approach, "Aerospace fabricators spend millions on prepreg each year, and without this digital tracking, you end up throwing away 10-15% of your inventory every year because it's timed out. With this system, we've seen customers save as much as 80% of their material-spend."

Ben-Bassat points out that Plataine offers "software as a service," charging based on volume of data use, so that customers don't need to purchase the software. As to the paper travelers, all prepreg information is digital, so a digital trail — or thread — is created that can be checked, or printed, for each material roll when needed for audit purposes. Even something as simple as keeping track of tools can save a company significant cost, time and headaches, says Ben-Bassat. Plataine's Material and Asset

Tracker (MAT) 4.0 allows real-time visibility of layup molds, dies, tool kits, fixtures, trim/drill tools, and calibration tools, using a variety of RFID and bar-code technologies that monitor a tool's location, condition, conformity status and availability, as well as the number of autoclave cycles per tool. The software creates an automated log of each tool's use and maintenance data, and tells workers how to align the production schedule with the needed tools. "This offers a massive opportunity for improving quality control," states Ben-Bassat.

Steve Rodgers, head of smart manufacturing firm EmergenTek (South Jordan, UT, US), says, "We've already come a long way in automating composite processes, to bring part cost down. But remember that much of the touch labor in aerospace manufacturing is data collection and storage/retrieval of documents for quality control tracking, and errors can easily occur." Rodgers describes a case study for aerospace composite fabricator Composite Solutions (Sumner, WA, US), a company that has adopted EmergenTek's ZyynTek digital solution for material and asset monitoring/reporting.

Two years ago, Composite Solutions moved into its new facility and wanted a more streamlined, automated data collection and archiving system for its prepreg material management, with a goal of decreasing material waste. In collaboration with Rodgers' team, a sensor system was engineered to:

1) Automatically collect the data normally collected by chart recorders
2) Send that data to a Web-based portal for permanent archiving
3) Create an intuitive and user-friendly portal accessible by multiple parties
4) Design the archived records for ready retrieval for audits
5) Enable automatic e-mails or text message warnings if sensors began to approach specification limits to preclude a manufacturing problem before it occurs.

For example, the company's large, walk-in freezer was divided into zones, with battery-powered sensors placed within each to monitor temperature and humidity as well as differential pressure. The same zone approach was taken for cleanrooms and the quality lab. The company's two paint booths were monitored for temperature and humidity to correlate the material tracking data with paint quality. EmergenTek provided a private cloud storage system and the tracking software, with bank-style security that is accessible from anywhere in the world via computer, smart phone or tablet. The total cost of the digital sensor system was 25% of a typical manual monitoring system via clipboard and paper. "This is all in the spirit of AS:9100D, which was written around risk mitigation," says Rodgers. "Our sensor system mitigates risk at many levels, from human error to automated alerts when materials are going out of specification limits."

By augmenting the predictive and preventative nature of business, he adds, the resulting system has exceeded all objectives. A Composite Solutions spokesperson says, "When I compared the cost of the ZyynTek sensor system to manual monitoring, it was a no-brainer. The total installation took less than a day." In fact, the system has already paid for itself, in detecting a door-open fault on the freezer and alerting the company, which saved hundreds of thousands of dollars in materials that didn't have to be scrapped or recertified. Rodgers says ZyynTek can be used for prepreg tracking, oven and autoclave monitoring, and machine sensing, such as CNC cutting machines. "This type of system has virtually unlimited capability, in terms of data collection and in ease of collating and presenting the data for audit requirements." (See the Side Story titled "Data, process flow and the Theory of Constraints" on p. 32).

Steps to a smarter manufacturing floor

Industry 4.0 can be adopted in stages on the manufacturing floor as well, says Ed Hilligrass, executive VP at Diversified Machine Systems (DMS, Colorado Springs, CO, US). DMS has developed native software programs for its customers that integrate each machine's control system, supplied by Fagor Automation (Elk Grove Village, IL, US), to power its Industry 4.0 technology. "Every machine manufacturer has some form of interface for machine communication — for example, MTConnect [see Learn More] that links machines to the IIoT via a standard protocol. Our machines don't require MTConnect — we work directly with a software supplier on a system that, coupled with our software, provides better accuracy and more complete integration."

The Manufacturing Data Management (MDM) software, which DMS sells with every machine, was born from a joint development with CIMCO, a trusted partner based in Copenhagen that DMS has worked with for about 8 years. The software enables connected machines to communicate during various manufacturing steps by generating and collecting data including part identification via barcode or RFID, part position, tool wear, interactive job and resource planning and more. "This system allows collection of and access to virtually unlimited amounts of data effectively to support »

SIDE STORY

Industry 4.0: A rose by any other name ....

Industry 4.0 or smart manufacturing is a collective term that embraces automation, data exchange and manufacturing technologies, enabling the Fourth Industrial Revolution. It has been enabled by the growth of the Internet of Things (IoT), now the Internet of Services, and its subset, the Industrial Internet of Things (IIoT), a term reportedly coined in the US by General Electric (Boston, MA, US) around 2011 to mean interconnected smart manufacturing machines and devices. The term Industry 4.0 originated as a German government "Future Project" (Industrie 4.0) in 2011, with a goal that included not only smart factories, but also multiple *interconnected* factories and even entirely linked geographic regions, including utilities, communication networks and "smart" cities. In China, it is referred to as wù lián wăng (物联网).

SIDE STORY

Industry 4.0: Sources for software and services

Although it can't be declared an exhaustive list, the following is a compilation of the Industry 4.0-aware suppliers *CW* turned up during its research on the 4.0 trend. These vendors reportedly provide some or all of the computer/software-based tools necessary to create the "digital twin" that mirrors the physical manufacturing plant and autonomously keeps it in operation with little necessity for human intervention.

Supplier	Product(s)
Anark Corp. (Boulder, CO, US)	Anark Core and MBEWeb software
Bosch (Stuttgart, Germany)	i4.0 solutions
CIMCO (Copenhagen, Denmark)	CIMCO Software 8
Dassault Systèmes (Waltham, MA, US)	3DExperience platform
EmergenTek (South Jordan, UT, US)	ZyynTek sensors and software
General Electric (Boston, MA, US)	Predix Industrial IoT platform
iBASEt (Foothill Ranch, CA, US)	Solumina MES and MOM software
IBM (Armonk, NY, US)	Enterprise Asset Management (EAM)
Memex (Burlington, Ontario, Canada)	Merlin MES Software
Plataine Technologies Ltd. (Waltham, MA, US)	MAT 4.0 and manufacturing optimization software
PTC (Needham, MA, US)	ThingWorx platform
SAS Institute Inc. (Cary, NC, US)	Analytics for IoT
Siemens PLM Software (Plano, TX, US)	PLM and MOM software portfolios

and manage production OEE [Overall Equipment Effectiveness]," he adds.

The system allows, for example, a part mold to be affixed to a tool plate, where it supports the part through the machining process. After the initial setup, the fixture is coupled via sensors with a robotic shuttle that moves the fixture both in and out of the work envelope. When prompted, the shuttle retracts the fixture onto an automated guided cart, which travels to the next step in the assembly process, say, for installing fasteners or other secondary processes. A series of integrated sensors and Fagor program logic detects fixture connection at each machine, and the machine software downloads the appropriate program for the correct operation for that part. After the machining process is complete, the software documents the details of the operation, and that documentation is captured by DMS' Manufacturing Data Management System, which resides on a network server. This process is repeated at each successive station, with no hands-on repositioning needed.

One DMS customer reports up to a 30% decrease in production time, improved quality and a more reliable down-stream assembly process, as the components move through more than 13 different stations/positions as a result. "The benefit here is that the hands-on fixturing of the part only has to be done once. The machine controller, coupled with the software, detects the part position accurately. You're reducing manufacturing time and eliminating the drudgery of repetitive touch labor and getting a more accurate part," says Hilligrass. He adds that DMS also is a partner with Autodesk Inc. (San Rafael, CA, US) to provide customers On-Machine Verification (OMV) using Autodesk's PowerInspect multi-device 3D measurement software, which can interface with inspection methods, such as machine tool touch probes or touchless probes, such as DMS' Visioning System. "The collected manufacturing data, essentially a data mine, makes your company more knowledgeable, since you can track your efficiency and identify any problem areas."

Oak Ridge National Laboratory's (ORNL, Oak Ridge, TN, US) Carbon Fiber Technology Facility (CFTF) is implementing smart manufacturing for its fiber production, says Yarom Polsky, who is ORNL's lead in the Smart Manufacturing Innovation Institute, one of nine manufacturing hubs (similar to IACMI) aimed at improving the US economy through more efficient manufacturing. The Smart Manufacturing Innovation Institute, comprising nearly 200 partners from academia, industry and nonprofits, is led by the Smart Manufacturing Leadership Coalition (SMLC) in partnership with the US Department of Energy (DoE), with the goal of streamlining complex manufacturing systems to radically improve advanced manufacturing. "Smart manufacturing is about real-time integration of advanced measurement, modeling, simulation, and controls into manufacturing process design and execution workflow," says Polsky. "Each of these activities are done independently, now, in a sequential manner. We want to bring them all together seamlessly." »

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Read this article online | short.compositesworld.com/CompInd40

Read more about the digital twin concept online in the *CW Blog* titled "Digital twin, digital thread and composites" | short.compositesworld.com/DTwin

IACMI's Dale Brosius comments at length on the implications of Industry 4.0 for composites in a recent column written for *CW*, titled "Get ready for Composites 4.0" | short.compositesworld.com/Comp40

One exemplar of Industry 4.0 actualization was visited by *CW* and written about in *CW's* "Plant Tour: BENTELER SGL, Ort im Innkreis, Austria" | short.compositesworld.com/BentelerSG

One *CW* excursion to a composites manufacturing facility afforded a visit to a plant to view Plataine's digital toolbox in use. See "CW Plant Tour: Composites Technology Center, Stade, Germany" | short.compositesworld.com/CTCTour

Plataine president/CEO Avner Ben-Bassat recently gave *CW* readers guidance for "Applying the Internet of Thing to composites production efficiency" | short.compositesworld.com/ApplyIoT

CW's journalistic cousin, *Modern Machine Shop*, featured the following editorial by its editor, titled "Seven things to know about the Internet of Things and Industry 4.0" | short.compositesworld.com/7Things

The following links provide access to additional online information or data about topics touched on in this article:

Siemen's automated factory in Amberg, Germany | short.compositesworld.com/SiemensAG

GE's Brilliant Manufacturing site | short.compositesworld.com/GEBrillMan

SME Advanced Manufacturing.org IoT survey | short.compositesworld.com/IoTsurvey

Machining News (technology portal Web site) on smart Schuler hydraulic compression press for composites manufacturing at IACMI | short.compositesworld.com/MachNews

MTConnect, an initiative led by the National Center for Defense Manufacturing & Machining (Blairsville, PA, US), which provides structured data protocols for connected devices | www.mtconnect.org

Composite Solutions Case Study | zyyntek.com/case-study.html

At the CFTF, Polsky describes the steps taken so far to introduce smart carbon fiber manufacturing: "We're developing in-line ways to measure the fiber properties. Non-contact, non-invasive spectroscopic techniques, electromagnetic property measurements, and 3D scanning laser Doppler vibrometry (LDV), the latter developed by Vanderbilt University, are being investigated and tested. If we know the machine parameters, and can correlate them to the in-line measurement data and process models, that will give us the ability to adjust process settings during manufacturing in real-time to ensure we're producing fibers with the properties that we want." In addition to developing the measurement techniques, Polsky says a group within ORNL also is building a physics-based model under another DoE-funded program to simulate the processing of the fiber, in effect, a carbon line digital twin, which requires considerable computing power, he adds.

When the HPC physics-based model is complete, a "reduced order model" can be generated to relate fiber condition to control parameters. These likely will be parameters such as fiber feed rate, oven temperatures and tension, says Polsky. "We'll be coupling the in-line measurements to control algorithms based on the model, to ensure more consistent and uniform product. Optimized data management is critical to achieving these goals. The CFTF offers a test bed to try these smart manufacturing techniques and demonstrate the value of IIoT."

"At IACMI, we recognize the need for smart manufacturing in composites. The work we have going on at Purdue University with the Composites Virtual Factory (cvfHUB) focuses on process simulation, and correlating the simulation with controlled manufacturing to develop predictive models that accurately describe the relationship between process variables like flow, temperature and pressure on the resulting physical state of the formed or molded product," says Brosius. "On another front, we are working at Vanderbilt University to develop upstream process sensors that give us early indications of the state of a material, and relay that to a data collection system that reduces the data to help us understand what is happening. We have deployed some noncontact sensing developed by Vanderbilt on the PAN spinning line at University of Kentucky and the CFTF at Oak Ridge, with very promising results." He adds that IACMI is in discussions with the Smart Manufacturing Innovation Institute to look at how best to work together to provide test beds for the innovative work they are doing.

Going all in?

Information technology research and advisory company Gartner Inc. (Stamford, CT, US) predicts that by 2020, there will be 21 billion connected things within the IIoT. Yet one 4.0 solutions provider, Memex Inc. (Burlington, ON, Canada), claims 97% of manufacturing companies currently aren't yet employing Industry 4.0. That said, DMS' Hilligrass points out, "Every client we're meeting with is asking about Industry 4.0 and how they can improve their manufacturing practices."

The degree of adoption of smart manufacturing depends, continues Hilligrass, on the business sector, company size and customer base, and is perhaps more important for customers who require part and quality traceability: "The tools and capability are there now — slow adoption of the technology by companies is the holdup."

SGL's Cohen says, "People tend to think that as a program ramps up and rate increases, the cost per part will go down. But that's not true, if you're still using manual processes — it doesn't work. You need the digital thread to remove the tedium and the potential for mistakes."

Ultimately, adoption of Industry 4.0 tools and techniques has the potential to significantly reduce composite part cost, while improving quality and cutting waste and scrap. Concludes ORNL's Polsky, "This is where the future is going. Applying smart engineering, will enable lower cost composite materials and processes." CW

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Plant Tour: FiberCore Europe, Rotterdam, The Netherlands

From debond-proof bridges to cost-saving infrastructure rehab, InfraCore technology is establishing composites as the fourth major construction material.

By **Ginger Gardiner** / Senior Editor

Industrialized composite infrastructure production

FiberCore Europe has fine-tuned industrialized production of large composite bridges and infrastructure components in its 7,000m[2] facility on the Nieuwe Maas River.

Source (all images) | FiberCore Europe

» FiberCore Europe, situated on the Nieuwe Maas River, a few miles from the Port of Rotterdam in The Netherlands, has distinguished itself in the world of composite infrastructure. Established in 2008, the company has fabricated and installed more than 500 composite bridge structures, including composite bridge decks that are rated in the highest load class recognized in the European Union (EU) design codes (60,000-kg traffic load). It is also the source of the world's largest fiber-reinforced plastic (FRP) waterway lock gates for shipping canals (see Learn More, p. 45).

CW visited the FiberCore Europe facilities, guided by company founder Simon de Jong, who asserts, "We've changed the whole logistics and building process for bridges and other infrastructure." A prime example is the oddly shaped, 18m-span Krụisvaartbrug bridge, in Utrecht, The Netherlands (Fig. 1, p. 41), which features a 90-cm thick composite deck. "We put it into place in 10 minutes," he recalls. "Everything was prefabricated, including the aggregate surface, so no extra steps were needed."

De Jong says the same approach was used in the 142m-long hybrid composite deck/steel truss bridge that now spans the A27 motorway near Utrecht, which features two 71m spans between supports, and the previously noted 13m-tall, 6m-wide Wilhelminakanaal lock gates near Tilburg. "We try to prefabricate as much as possible," he explains. "For the lock gates, it is not just the door panels, but also ancillary parts and attachments, in order to greatly simplify installation. It's the light weight of our solution that enables this modularization and prefabrication."

This lightweighting is possible due to composites, but the high load-bearing capabilities and long spans are a product of the company's patented InfraCore technology (see Learn More and the Side Story titled "InfraCore: Bio-logical structure," on p. 42).

FiberCore Europe is now working to introduce InfraCore technology into new applications, including liquid natural gas (LNG) tanks, ships, wind blades and aerospace structures.

InfraCore inside

Examples of what InfraCore technology achieves include an all-composite vertical lift bridge in Oosterwolde, located in the Dutch province of Friesland (Fig. 1). The 11.2m-wide bridge, which spans 12m, is rated for 60-MT of traffic and integrates the counterweight for the lowering mechanism inside part of the composite bridge deck. "The designers loved this not only for the clean aesthetics," explains de Jong, "but it is a financial benefit as well because ballast cellars are terrible for maintenance." Eliminating ballast cellars, where counterweights sink when the bridges open, results in huge cost and time savings. Another Dutch lift bridge, built in Muiden and constructed as a single module, was so lightweight that it was easy to lift with a standard hydraulic system and no counterweight was needed. "We installed the whole lifting piece in 30 minutes," notes de Jong, adding, "the bridge also goes up and down much faster than its heavier steel predecessor."

In general, FiberCore Europe's composite lift bridges are 20-30% less expensive than steel alternatives. Cost savings are also reaped in static bridges. Lightweight composite components reduce or eliminate the need for supports and modifications to existing structures. A case in point is the 17.5m long, 2.5m wide composite bridge in Ghent, Belgium, which connects two of the oldest buildings in the 17th Century city center. "There was no need for structural modifications to the buildings," says de Jong.

Another example, and possibly the beginning of a new bridge design paradigm, is the 20m long, 1.9m wide bridge on the Excercitiesingel in Rotterdam (Fig. 1, bottom photo). It is 50% less expensive than steel because it was designed based on *strength*, not stiffness. Normally, design guidelines for FRP bridge structures mandate stiffness-driven designs, which can increase weight unnecessarily. "A standard InfraCore bridge designed on stiffness can be up to 10 times stronger than needed," explains de Jong. "Due to FiberCore Europe's significant bridge construction experience, we asked the bridge's design engineers to allow us to build the bridge where it is still five times stronger vs. steel but not stiffness-driven." The resulting all-composite design features an aesthetic geometric lattice railing — designed and produced by innovative FRP company Jules Dock (Rotterdam) — and a bridge thickness of only 25 cm, making it the most slender FRP bridge in the world (ratio 1:68). "After the bridge was finished in our facility, we could load it and deflect the deck approximately 1m," he notes. That had been anticipated. "Once we installed it, anchoring each end in concrete, it was sufficiently stiff for the end-use and pedestrian/cycling loading per its rigorous design." »

FIG. 1 One composite construction, many infrastructure solutions

The InfraCore Inside technology enables large, prefabricated composite bridge decks, bridge supports and other infrastructure applications that have no risk of interlaminar cracking or debonding. Examples of resulting lightweight and installation-friendly solutions include (from top to bottom) the Kruisvaartbrug bus bridge, A27 viaduct, lifting bridge in Oosterwolde and the world's most slender FRP bridge on Rotterdam's Excercitiesingel.

Scalable, repeatable process

With that as introduction, *CW*'s tour begins in the administration and engineering offices at the 7,000m^2 facility's east end, where FiberCore Europe's seven engineers, most trained in civil or mechanical engineering, work with clients, architects, government engineers and regulatory authorities to ensure composite designs meet clients' requirements, then prepare drawings for fabrication and installation. A few are composites engineers but others have received an education in FRP since being hired.

De Jong leads the way out into the large open production space to the building's west end. This is where polyurethane and other types of foam core are received as well as glass fiber reinforcements. The foam comes with grooves cut to aid in molding curved shapes. De Jong explains that sometimes the foam is perforated as well to aid resin flow during infusion molding. "All of that is designed-in per bridge, depending upon requirements."

De Jong walks back east to an adjacent area where glass fabrics are unrolled and patterns are cut. FiberCore Europe uses mostly noncrimp fabrics and a smaller number of chopped fiber mats. Here, precut foam core and glass reinforcements are preassembled, marked and stacked in preparation for each successive project. Every material is tracked, and each pre-assembly is assigned a number with the material data attached to it (e.g., batch and lot of foam and glass, etc.).

Continuing east, de Jong points out two large articulated molding tables — the longest is 55m by 6m — each comprising a steel plate on top of adjustable steel scaffolds. These can be reconfigured to mold bridge decks and support structures (Fig. 3, p. 42). Mold surfaces are prepared with a release film/foil. Fabrics are then laid onto the molding tables, followed by placement of the glass-wrapped beams and then the top skin fabrics. The layup is vacuum bagged and resin is measured and mixed for infusion. Much of the resin that FiberCore Europe uses is supplied by Royal DSM (Heerlen, The Netherlands).

Returning to the building's east end, de Jong points out two short (9m long) bridges in finishing stages. One is receiving a mix of aggregate and resin to provide its final surface (Fig. 4, p. 42). "This small span we infused in one hour, but if we shoot a span 10 times that long, we still infuse it in one hour," he says. "This is because we use a very standardized, repeatable process. We have built over 700 structures and have never had any problems with infusion," he claims, noting that the shorter infusion time also reduces risk. "The more time during your process, the more variables and unplanned scenarios. We impregnate all of the part in one flow, at one temperature, so the process is more stable."

Although the small bridges were to be shipped fully prefabricated, ready for installation, for larger projects FiberCore Europe also produces bridges in sections that will be shipped separately, then installed side-by-side and connected on site. During *CW*'s tour, eight sections were being fabricated for a 110m-span by 7m-width pedestrian bridge for the city of Amsterdam. For this project, the composite was chosen to replace degraded timber decking. The rebuilt bridge will reuse the existing primary concrete structure, which is still in good condition. "We will have the sections finished as much as possible and then complete the construction on site in Amsterdam," de Jong explains. He notes that with its current production setup and available space, FiberCore Europe can build as many as 140 bridges per year. "Our process is very scalable and easy to replicate," he observes, adding that the company is looking to license its technology to a series builder/partner in the US to serve the North American market.

Future of FRP bridges

There is a big discussion in Holland and Europe right now about the lifecycle analysis (LCA) of FRP, says de Jong. "Ten reports say it is better for nature, while there is a significant and strong lobby against it," he adds, noting this is mostly from the concrete lobby

SIDE STORY

InfraCore: Biological structure

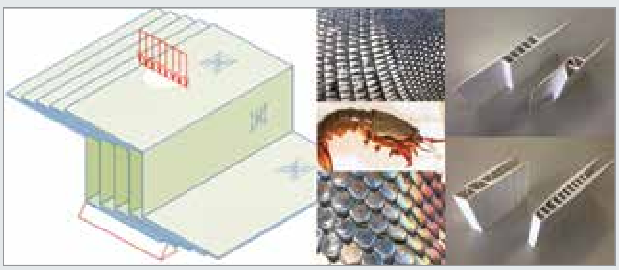

FIG. 2 InfraCore Inside

The InfraCore Inside technology is based on oblique layered materials, like those found in armadillo and lobster exoskeletons and snake scales, providing a strong, lightweight structure with integrated resistance to delamination, impact, blast, fatigue and even fire.

FiberCore Europe (Rotterdam, The Netherlands) claims that its composite structures — despite sometimes long spans between bridge supports — won't crack or debond and that any delamination from impact will not propagate, as demonstrated by large-scale testing with tire-sized loading up to 13.5 MT. After 30 million cycles in testing, which simulates a 100-year service life, there was reportedly no propagation of damage, and strength and stiffness were the same as before damage. "We do not use FRP unless we can prove there is no interlaminar cracking or debonding," says FiberCore Europe co-founder Jan Peeters, who credits the test performance and on-the-job results for his company's products thus far to oblique layered materials (Fig. 2, above). Similar to biological structures, such as fish and reptile scales and exoskeletons, such as that on the lobster and armadillo, this construction provides the stiffness of sandwich or truss construction and aids in load distribution while preventing the spread of damage from localized point loads or impacts.

"It delivers heavy-duty, maintenance-free composite plate structures that are lightweight and yet have integrated resistance to blast, impact, fire and fatigue," he claims, adding, "To do all of this simultaneously is unique. The fire resistance comes with or without additives in the resin because the fibers are locked together, so even if the resin burns away completely, the structural load path is still there." This was proven during fire-resistance testing of bridge structures. "They must last for two hours," explains Peeters, "but after three hours, our structures were still there."

FIG. 3 Massive tables for molding

A large, infused composite bridge structure is shown as it is moved from one of FiberCore Europe's large, articulated steel molding tables.

FIG. 4 Finishing & fixtures

After infusion, bridge decks are moved to the east end of the building to receive railings, hardware and perhaps other fixtures as well as their final surface finish, typically aggregate mixed with resin.

FIG. 5 Halting the march of harbor corrosion

FiberCore Europe has produced more than 30 composite bridges for the Port of Rotterdam this year (two are shown above), just a fraction of the 900 steel truss bridges in Rotterdam harbor that have issues with corrosion and deterioration.

because FRP is becoming strongly competitive in their markets. "However, our cofounder Jan Peeters won Engineer of the Year in 2016, recognized for his influential work in FRP infrastructure. He was nominated, in fact, by concrete and steel engineers. So I think the whole industry realizes that FRP is the future."

Bolstering FRP's positive outlook is the current trend to replace steel and aluminum harbor bridges or gangways with composites (Fig. 5, above). "Every harbor in the world has these bridges, going from the land to the docks," says de Jong. "There are 900 steel truss harbor bridges in Rotterdam harbor, and they all have this issue of corrosion and deterioration. This year, FiberCore Europe has produced more than 30 harbor bridges for the Port of Rotterdam."

In spans of less than 25m, however, composites still lose out to lower-cost steel. Composites win for 20-50m spans because their lower weight requires fewer support columns. In some versions, FiberCore Europe has matched the weight of the pontoon that the gangway/bridge ends upon so that it does not push the pontoon down, but allows it to move with the rise and ebb of the tides. These designs also have lights integrated into them and use a bio-based polyester resin from Polynt (Scanzorosciate, Italy) for an overall environmentally attractive solution.

FiberCore Europe has extended this bio-based concept via the bio-basalt-balsa (B3) bridge in the Schiphol Logistics Park, adjacent to Amsterdam's Schiphol Airport. Designed to be eco-friendly and last for >100 years, this 15m-long, 2m-wide all-composite pedestrian bridge maintains the bio-polyester resin but switches out fiber-glass for basalt fiber reinforcement, made from igneous rock and offering greater strength and stiffness without a major cost uptick. The bridge also features a lightweight deck of balsa-cored composite sandwich construction, and was built in cooperation with Dutch engineering firm Royal Haskoning DHV (Amersfoort, The Netherlands), basalt fiber supplier Mafic S.A. (Kells, Ireland) and balsa core supplier Airex AG (member of 3A Composites, Sins, Switzerland), with core CNC-machined by Poly Base (Tilburg, The Netherlands).

Although FiberCore Europe sees continued strong growth in composite bridges and other infrastructure, it also sees a serious »

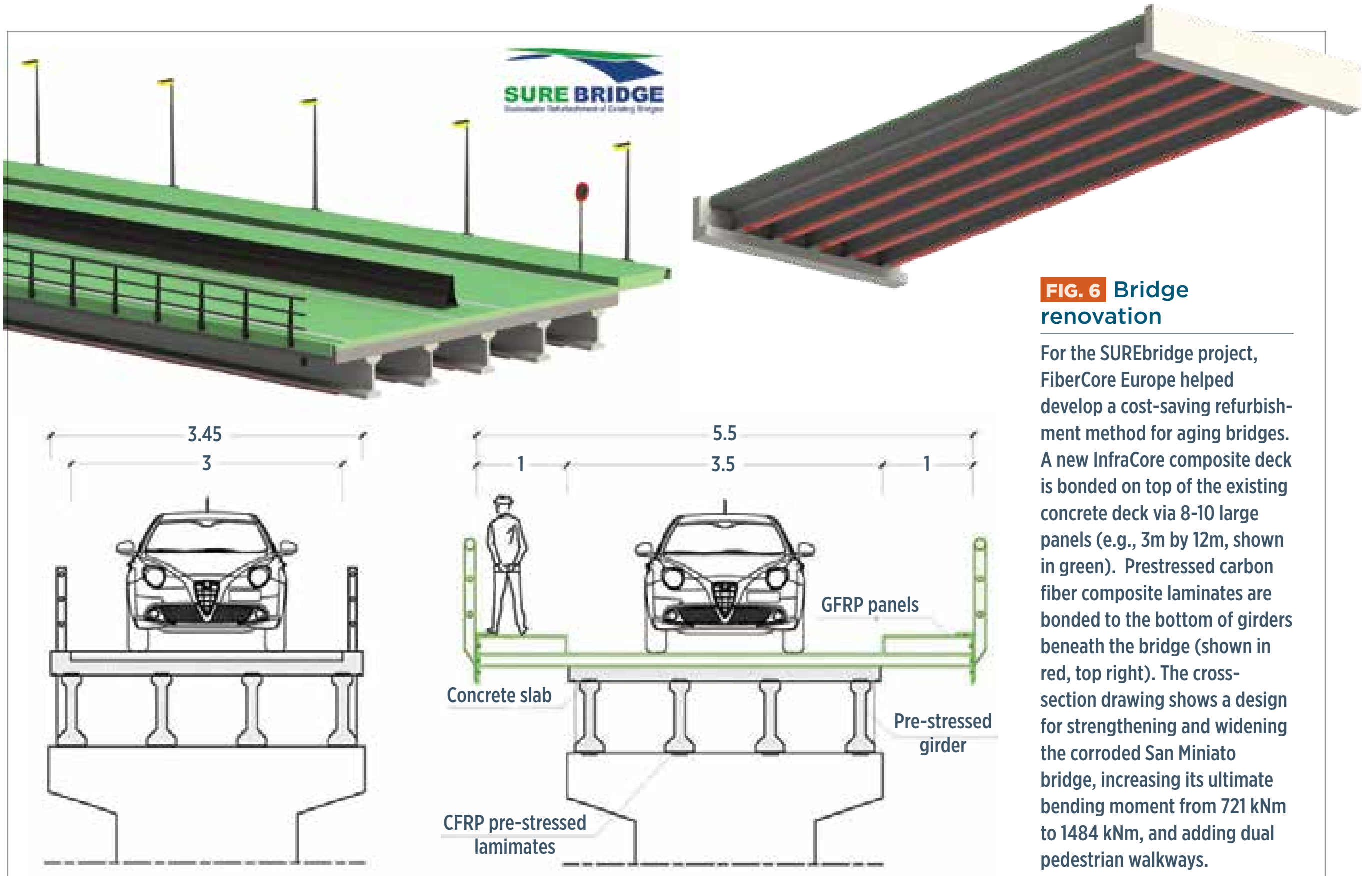

FIG. 6 Bridge renovation

For the SUREbridge project, FiberCore Europe helped develop a cost-saving refurbishment method for aging bridges. A new InfraCore composite deck is bonded on top of the existing concrete deck via 8-10 large panels (e.g., 3m by 12m, shown in green). Prestressed carbon fiber composite laminates are bonded to the bottom of girders beneath the bridge (shown in red, top right). The cross-section drawing shows a design for strengthening and widening the corroded San Miniato bridge, increasing its ultimate bending moment from 721 kNm to 1484 kNm, and adding dual pedestrian walkways.

threat from builders who do not use structurally sound designs and fabrication methods. "We need competitors in infrastructure to build the market," de Jong acknowledges, "but unfortunately, some are using technology that goes back to the 1990s and, already, some of their bridges have broken." He cites a bus bridge that broke after only two months in service. "I talked to the local government minister and explained why this happened and how he could rehabilitate the project, using FRP, but rightly. 'We will not use FRP again for 20 years,' was his response." Because of such incidents, FiberCore Europe is working with Dutch bridge authorities to write new FRP guidelines for infrastructure. "The whole reason our company exists is because there were failures in the other ways that have been used to make composite bridges," says de Jong. "We know there is a future for composites in these applications," he adds, "but that future must be safeguarded by making sure these materials are used correctly."

Sustainable bridge refurbishment

There may indeed be a very large future for composites in bridges, but perhaps even more so in refurbishment than original construction. FiberCore Europe is a key partner in the SUREBRIDGE project, one of nine scheduled for demonstration in 2017 as part of the Infravation Infrastructure Innovation Programme. Organized by transport ministries across Europe, Israel and the US Federal Highway Admin., Infravation's goal is to prove out innovative solutions for road infrastructure challenges. SUREBRIDGE was awarded US$1 million to demonstrate bridge and road refurbishment. FiberCore Europe's partners for this two-year project (October 2015-March 2018) include Chalmers University of Technology (Göteborg, Sweden) and AICE Consulting in conjunction with the University of Pisa, both located in Pisa, Italy.

According to project coordinator Dr. Reza Haghani of Chalmers University, there are more than 1 million bridges in Europe. More than half of them have been in service for 20-100 years (the oldest are railway bridges). Many are in need of repair/refurbishment, mostly due to issues with concrete decks. Refurbishment is estimated to cost at least €50 billion. SUREBRIDGE proposes to significantly reduce this figure by combining two technologies: an InfraCore composite deck adhesively bonded to the top of the existing concrete deck, with prestressed carbon fiber composite reinforcement to provide additional support underneath (Fig. 6, above).

"The width and depth of bridge decks to be rehabbed varies, but they typically comprise a concrete deck resting on concrete girders," explains FiberCore Europe head of engineering Martijn Veltkamp. "The deck is where the most refurb is required." It is also where traffic disruption must be minimized by making the refurb process as short as possible. "We have already proven that our InfraCore composite decks can be prefabricated and installed quickly," notes Veltkamp. "The design of each deck will be based on the current and future deck load requirements plus the degree of concrete deterioration."

Some concrete decks also will require strengthening underneath and, perhaps, even wrapping with composite laminate at the bottom of the girders. Although under-deck reinforcement may use glass or carbon fiber laminates, Veltkamp says rehab to girder bottoms will use carbon fiber-reinforced polymer (CFRP) and also will be prestressed. "Chalmers University has developed a method of prestressing CFRP," he explains. "This prestress is not applied all at once because that presents a high risk of peeling at laminate edges. Instead, it is applied gradually, over a long distance, producing a more robust construction for adhesion." Veltkamp notes prestressed CFRP is applied to the *bottom* of the girders, "because this is where strengthening is most efficient."

The technology for adhering the Infra-Core composite deck on top of existing concrete is also innovative. FiberCore Europe originally proposed its method of milling longitudinal grooves into the concrete, filling these with adhesive and then lowering the composite deck with molded-in ribs that mate precisely into the grooves, achieving a mechanical lock as well as adhesive bond. "We already complete this type of installation on an industrial scale," says Veltkamp. In 2016, a further development was completed to reduce environmental impact and worker health hazards — epoxy adhesive was replaced with high-performance mortar. Testing of prestressed, CFRP-strengthened girders was completed in 2017 at Chalmers University, showing a 150% increase in ultimate bending capacity, a reduction of crack width in the now-strengthened girders and improved durability.

The SUREBRIDGE project design case study involves a 60m long vehicle traffic bridge that comprises four spans of 15m each. It crosses the Elsa River in San Miniato, Italy. Its 3m-wide concrete deck is composed of a 160-mm thick concrete slab (cast on site) and four prefabricated, pre-stressed concrete girders 1m high and spaced 1m apart. Built in 1968, the bridge was inspected in 2006 and found to have concrete spalling, corrosion of steel rebar and breakage in some of the steel wires used for prestressing. Finite element models and analysis were completed for the original bridge and a strengthened design. The latter would feature a deck widened from 3m to 3.5m and an overall width expanded from 3.45m to 5.5m to allow for FRP pedestrian walkways on either side, next to the single vehicle-traffic lane. The SURE-BRIDGE design more than doubled the bridge's ultimate bending moment from its damaged state at 721 kNm to 1,484 kNm. Thus its benefits were demonstrated and design guidelines were developed for a representative application. »

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Read more online about FiberCore Europe's lock gates in "Fiber-reinforced polymer lock gates installed in the Netherlands" | short.compositesworld.com/FCElocks

Read more about FiberCore Europe's patented InfraCore technology online in the *CW* Blog titled "Disruptive composite infrastructure" | short.compositesworld.com/InfraCore

Discussion of these design guidelines and results from the full-scale testing campaign completed in 2017 were presented at a Sept. 1 workshop at Chalmers University and a Sept. 22 workshop at the University of Pisa. At both events, local road authorities expressed interest in SUREBRIDGE, yet stressed the importance of standard design guidelines to get such innovations formally accepted.

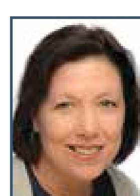
The workshops reviewed the comprehensive computer-aided design (CAD) models and standard operating procedure developed as an end-of-project deliverable. "The goal is to have a software design tool where you can fill in the bridge size and other parameters, and then analyze and evaluate the options for refurbishment, using the SUREBRIDGE solutions," says Veltkamp. "Transport authorities have already requested pilot projects to demonstrate the SUREBRIDGE technology ... and we are working to define these projects."

Another development with promise for the US is interest from the Army Corps of Engineers (Washington, DC, US). "They saw our lock gate projects and approached us, asking why our technology worked where others did not," de Jong relates. "We explained the issues with other composite technologies used in the past and also what we have now developed using InfraCore. So now we are starting a relationship and hope to work together in the near future."

Composites: Fourth major construction material

In a validation of the work that Fiber-Core Europe has done to prove composites' viability as a construction material, engineer William Schutte with the City of Rotterdam Engineering Office in the May 2016 SUREBRIDGE kickoff meeting described his vision for Rotterdam's future. It will include slender bridges without pile foundations, bio-based composite structures and composites in both floating infrastructures and normal building construction. Most importantly, he listed composites as the fourth major construction material (in addition to wood, metal and concrete), noting that hybrid solutions are typically the most optimal.

De Jong notes that since January 2017, the next applications of InfraCore have been developed through a separate entity, InfraCore Co. Ltd., also based in Rotterdam. The new company is closely connected with European research institutes and leading composites engineering firms. "We started with at least six major projects in progress," he adds. "The applications are wide ranging, but all heavy-duty structures that you would never imagine could be built using composites, spanning ships, wind energy and the military. The acceptance of FRP in heavy construction is now a fact. What we are doing is just the beginning of a huge development." CW



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Composites Events

Dec. 5-7, 2017 — Houston, TX, US
SPACECOM: Space Commerce Conference and Exposition
spacecomexpo.com

Dec. 6-7, 2017 — Cologne, Germany
7th Biocomposite Conference Cologne
biocompositescc.com

Dec. 6-8, 2017 — Pasadena, CA, US
Additive Manufacturing Americas 2017
amshow-americas.com

Jan. 23-24, 2018 — Long Beach, CA, US
1st Int'l Conference on Composites in Sports
jeccomposites.com/events/composites-for-performance-in-sports-2018

Jan. 31-Feb. 1, 2018 — Las Vegas, NV, US
Global Composites 2018
globalcompositesconference.com

Feb. 1-2, 2018 — Melbourne, VIC, Australia
20th Int'l Conference on Advanced Composites and Materials Engineering
waset.org/conference/2018/02/melbourne/ICACME

Feb. 14-15, 2018 — Dubai, UAE
CompIC Middle East 2018 Conference
mecompositesin.construction

Feb. 20-21, 2018 — Indianapolis, IN, US
SPE 2018 Thermoset Topical Conference – TOPCON
4spe.org/Events/event.aspx?EventID=82791

March 1-2, 2018 — Vienna, Austria
14th World Pultrusion Conference
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March 6-8, 2018 — Paris-Nord Villepinte, France
JEC World 2018
jeccomposites.com

March 6-8, 2018 — Osaka, Japan
4th Annual World Congress of Smart Materials
bitcongress.com

March 26-29, 2018 — Long Beach, CA, US
AeroDef 2018
aerodefevent.com

April 10-12, 2018 — Detroit, MI, US
SAE 2018 World Congress Experience
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April 10-12, 2018 — Knoxville, TN, US
Composites Recycling Conference
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April 30-May 3, 2018 — Denver, CO, US
AUVSI XPonential 2018
xponential.org/xponential2018/public/enter.aspx

May 7-10, 2018 — Chicago, IL, US
WINDPOWER 2018 Conference & Exhibition
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nasampe.org/events/EventDetails.aspx?id=699309&group=

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CW Ameri*mold*
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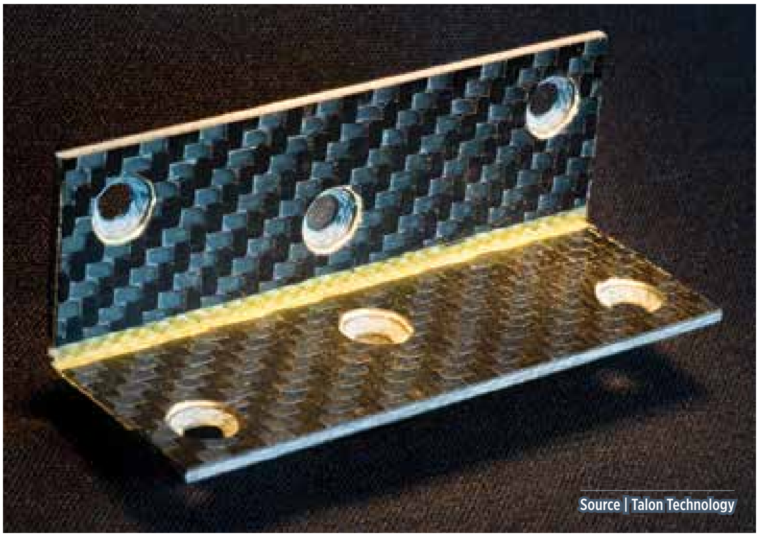
CARBON-KEVLAR HYBRID REDEFINES THE HINGE

Composite design outperforms comparable stainless steel at same price.

› Talon Technology (Brookvale, Australia) develops carbon fiber-reinforced plastic (CFRP) parts for manufacturers of volume consumer products, including furniture and sporting goods, and does a bit of work for the aerospace industry. But its Carbon-Kevlar Hinge was an in-house project, inspired by parts seen in model aircraft, where CFRP panels were scored and cracked to form hinges. "This reminded us of the original hinges, made from fabric and leather," recalls Talon CEO Geoff Germon. "Our idea was to develop a composite hinge without any metal, that would be super lightweight and also a solution for industries that can't use metal."


Source | Talon Technology

After two years of optimizing its performance and producibility, the final Carbon-Kevlar Hinge design has co-molded carbon fiber prepreg mounting plates — Talon calls them *wings* — with a gap between them in which the hinge's *flex unit* is formed. The wings might be woven carbon fiber/epoxy laminate or a hybrid glass and carbon fiber/epoxy laminate, while the flex unit is woven Kevlar impregnated with polyurethane. The wings are available in multiple sizes and the flex unit can be ordered as single Kevlar or for heavy duty with a double Kevlar layer. Most Carbon-Kevlar Hinge products are supplied in lengths ranging from 12 mm to 1,000 mm. But Germon cites the case of a 2.1m long hinge made recently for a carbon fiber composite motorhome.

"Our lightest duty hinge has a closed thickness of 1.6 mm, which is probably the thinnest hinge in the world that also has reasonable strength," says Germon. This hinge is, in fact, very strong, able to sustain a static load of 150 kg in a 50-mm long, 25-mm wide configuration. Germon asserts a similar metal hinge would hold roughly 50 kg. Although this thinnest hinge is designed for bonded assembly, thicker Carbon-Kevlar Hinge products can be bonded, attached with screws or both. "One of the issues with metal hinges is that you can't bond them, especially stainless steel," Germon notes. "Our composite hinges, however, are perfectly suited for adhesive bonding."

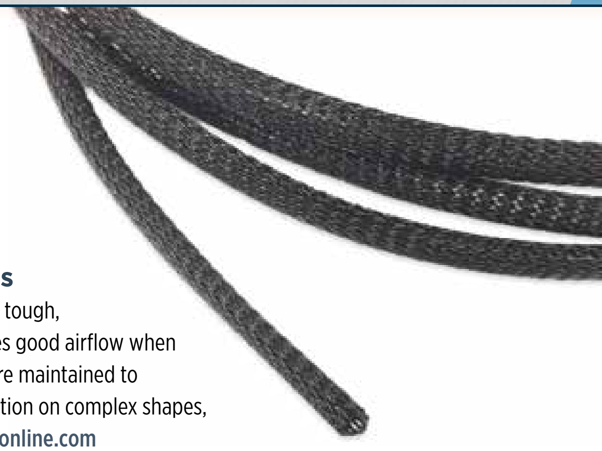
The Carbon-Kevlar Hinge also is not limited to flat surfaces. "We can mold complex forms into the CFRP wings," Germon explains. Talon Technology also can integrate multiple hinges into a CFRP part, using a one-shot process, that creates complex folding structures. "We have just produced a hinge with a wooden finish and are also producing a CFRP hinge with integrated fittings for electric cabling," he adds.

Germon sees the Carbon-Kevlar Hinge as the first commercial application of carbon fiber that can be a stock item on a retail shelf next to metal products. The hinge will soon be listed in the popular *McMaster-Carr* industrial supply catalog (**www.mcmaster.com**) and at the same price point as a high-quality stainless steel hinge, he adds, noting, "This is not being sold on the basis of it being carbon fiber, but instead, on its superior performance as a consumer item." Germon believes that the composites industry has educated the market to think that carbon fiber is always expensive. "In our case, it's not. We are re-educating the market to understand that it's a matter of how the carbon composite part is designed and how you use the fiber."

But the consumer isn't the only target. Aircraft interiors suppliers have expressed interest, and a prestige auto manufacturer is planning to use the Carbon-Kevlar Hinge in an upcoming model's seat application. "We are working to develop the necessary impact and shock-test data now," says Germon. Noting that one of The Boeing Co.'s (Chicago, IL, US) Tier 1 interior suppliers has a 700,000-cycle test for hinges, Germon reveals, "We just put our hinges through one million cycles of this test, which uses very fast cycling through an 80° arc, roughly 340 cycles/minute, which is more than 5 cycles per second. That would normally kill most metal hinges, but ours," he claims, "showed no change whatsoever."

Germon emphasizes that hinge hardware is a multi-billion-dollar market. "We need to reach out and educate industrial designers and engineers about composites," he argues.

Note: Talon Technology's Carbon-Kevlar Hinge is one of five finalists for the 2017 CAMX award for Unsurpassed Innovation and will be on display in the awards area at the back of the Exhibit Hall. CW



New Products

» VACUUM-BAG PROCESSING ACCESSORIES

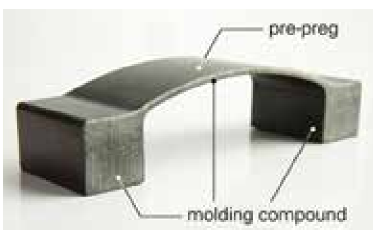
Braided breather cord for vacuum-based processes

Airtech International Inc. (Huntington Beach, CA, US) has developed Airpath MD, a tough, lightweight braided breather cord. The open weave construction reportedly provides good airflow when used as an edge breather around a vacuum-bagged part, ensuring vacuum levels are maintained to achieve good part quality during curing. Features include flexibility for easy application on complex shapes, and good temperature resistance for performance at elevated temperature. airtechonline.com

» FIBER/RESIN COMPOUNDS & PREPREGS

Prepreg developed for compression molding

Norplex-Micarta (Postville, IA, US) has introduced EnableX, a continuous fiber prepreg that can be co-cured in a multimaterial molding system to produce near net shapes. EnableX materials are specifically designed for compression molding and tested by Norplex-Micarta to ensure compatibility with the process. In addition, Norplex-Micarta's in-house laboratory and development capabilities allow for new concepts to be prototyped, or datasets to be developed to support specific design criteria. EnableX has been verified on several epoxy and phenolic resin systems, with more in development. Reinforcement options include natural fibers such as cotton or paper, carbon fiber, glass fibers and fibers that significantly alter the behavior of the material such as PTFE or thermoplastics. norplex-micarta.com



» VIRTUAL TESTING & SIMULATION SOFTWARE

Composites process simulation software update

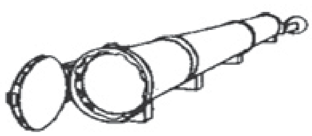
ESI Group (Paris, France) has released ESI PAM-COMPOSITES 2017, the latest version of the company's process simulation software for the manufacture of composites. PAM-COMPOSITES 2017 targets thermoformed acoustic and cosmetic multi-material components typically used in automobile and aircraft interiors. This new version gives users the ability to determine the noise and vibration response of the manufactured product by predicting the stiffness and thickness in each location of the formed part. Typical defects, such as tearing and skin texture modifications induced during manufacturing, can also be anticipated and corrected through simulation. Also new is a grid tracing tool that allows users to analyze the length variation on each segment of the grid as they would do on physical prototypes. Moreover, the new element-elimination tool allows the visualization of physical holes or fiber separations generated during the thermoforming of composite products. esi-group.com

» CNC MACHINING EQUIPMENT & ACCESSORIES

Abrasive waterjet cutting systems

OMAX Corp. (Kent, WA, US) has launched the GlobalMAX line of abrasive waterjets capable of cutting virtually any material. The company says the GlobalMAX product line was created to extend its waterjet engineering and manufacturing technology base to more customers. The line features direct-drive pump technology, easy-to-use software and motion control technology. The company also has developed ProtoMAX (see inset), a compact, self-installed, abrasive waterjet cutting system for prototyping and relatively low volume cutting of almost any material of less than 50 mm thick. ProtoMAX is designed for small shops, engineering classrooms, makerspaces and personal use, as well as large shops and fabricators that need occasional waterjet capabilities to complement their other cutting systems. ProtoMAX offers 30,000 psi cutting power with a 5-hp pump and can precision cut composites, metals, glass, granite, plastic, wood and more. It plugs into a 240V AC outlet and does not require hard-wiring. The pump and cutting table are on casters for easy relocation. Work material is submerged under water for clean, quiet cutting that won't disrupt a shared work space. The programming of part files and the cutting operation are controlled by Intelli-MAX software, which is derived from the company's industrial waterjet systems software. omax.com

MANUFACTURING SUPPLIERS



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SHOWCASE

Audi R8 seat wall: A prelude to production

Audi takes it upon itself to design and develop carbon fiber composite structures that, the automaker hopes, will enter high-rate production.

By **Jeff Sloan** / Editor-in-Chief

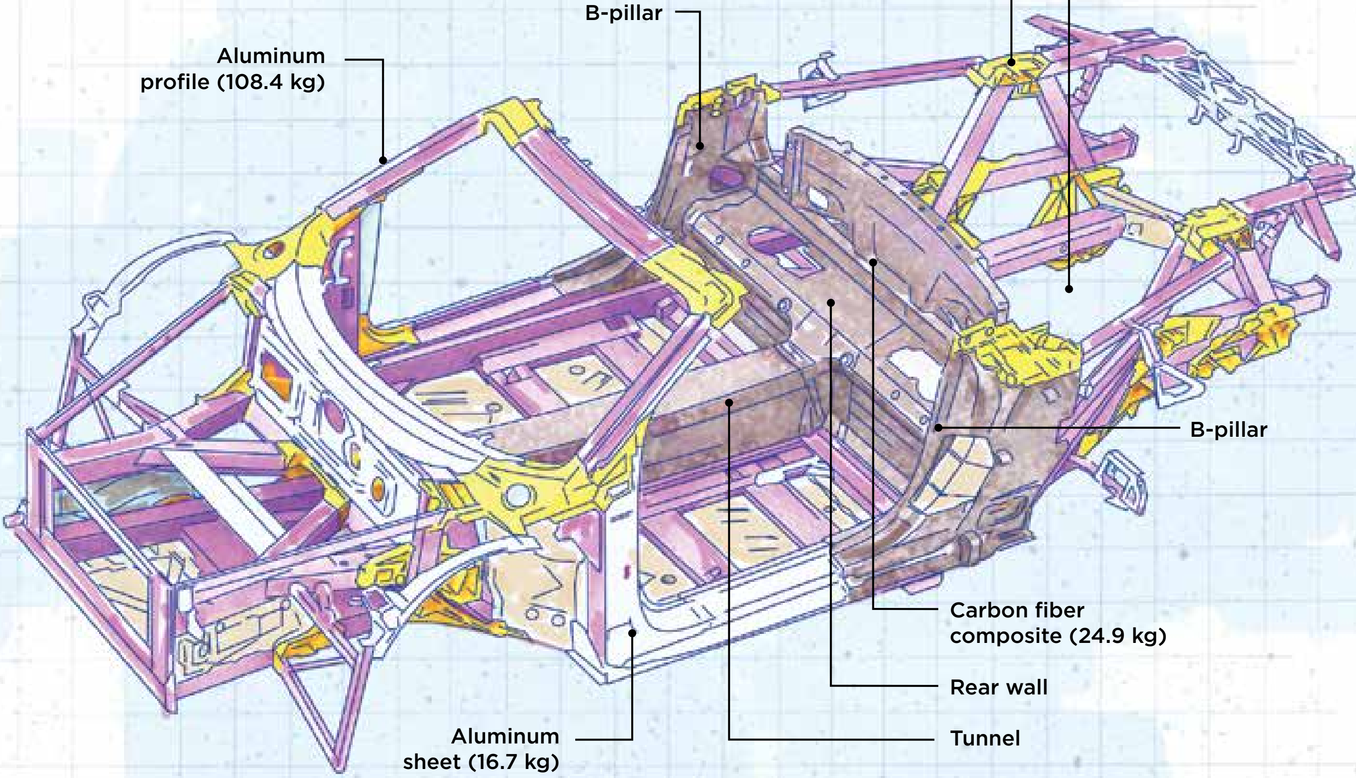
» High-volume, high-rate automotive manufacturing has been, for many years, the Holy Grail of the composites industry. Today, autocomposites is arguably the second-most important target market for materials suppliers and parts manufacturers in the advanced composites segment, nearly on par with the aerospace industry. But putting composites on the same material palette as the auto industry's still-preferred steel and aluminum will take time and effort. Those who would do so face formidable challenges: Composites' complexity, the result of its combination of fiber with matrix and all that implies for its potential performance parameters, present inherent design and simulation difficulties. Composite materials, unlike steel and aluminum, have yet to be standardized. Then there are the relatively high costs and relatively long cycle times. Still, auto OEMs are highly motivated to take weight out of vehicles, and for that reason alone they are clearly willing to give composites a chance.

For automotive OEMs, the question is, *Where do we start?* One of the most popular and sensible strategies is to begin with a low-volume application and evolve to high-rate production. This is what Audi (Neckarsulm, Germany) had in mind about seven years ago, when development began on its Modular Sports-Car System (MSS), designed for use in the Audi *R8 Coupe*, *R8 Spyder*, R8 *LMS* (race car) and the Lamborghini *Huracan* — all two-seaters, with rear-mounted engines.

Molding in vehicular stability

Auto OEM Audi (Neckarsulm, Germany) worked for several years to determine where and how to apply composites to the Modular Sports-Car System (MSS) on its 2016 *R8 Spyder* and *Coupé*. The car's rear wall with integrated B-pillars, and its CFRP driveshaft tunnel are molded from a carbon fiber composite. In this car, a convertible, the rear wall separates the passenger compartment from the rear engine compartment, and absent the roof structure, it and the tunnel must provide the car's entire mid-vehicle stiffness and structural support. Source | Audi

The MSS was envisioned as a tool for applying advanced materials to the body-in-white (BIW) to reduce mass and improve efficiency, particularly as vehicles evolved toward electrification. David Roquette, a technology development CFRP specialist at the Lightweight Design Center Audi (Neckarsulm), says the first-generation *R8* was aluminum, but Audi decided the next generation of the MSS program's applications should use carbon fiber composites. The question was where to apply it. This, says Roquette, launched a three-year BIW assessment effort to find an



DESIGN RESULTS | Audi *R8 MSS* CFRP Rear Wall and Tunnel

- Body-in-white load cases indicate composites as the most effective materials for use in rear wall, B-pillars and tunnel structures.
- Moldable 3D foam core optimizes strength-to-weight balance while polymethacrylimide material resists core crush.
- Sandwich construction reduces carbon fiber volume, curbing cost, and dictates low-pressure, high-speed RTM process.

Illustration / Karl Reque

answer. He and his colleagues used an in-house-developed optimization software package to identify 23 load cases on the BIW, and then identified the BIW parts that experience the most anisotropic stresses, and, thus, were deemed best suited for composites.

"However, it was not just stress," Roquette notes, "but economic as well. Can we build it? Do we have the technologies? Does it make sense in terms of cost and weight?" The parts that met these criteria changed as development work evolved, but revolved around the driveshaft tunnel and the rear wall, which separates the passenger compartment from the rear engine compartment. Applying carbon fiber composites here on the 2016 *R8 Spyder* and *Coupé*, says Roquette, offered a substantial improvement in torsional stress and vehicle stiffness and a good opportunity to reduce vehicle weight.

Designing for load cases

Roquette's colleague Felix Diebold, also a technical center CFRP specialist, says that when Audi's composites research first focused on the previously mentioned 23 load cases, the company was looking particularly for opportunities where composites would enhance the BIW's torsional stiffness and reduce weight, thereby boosting overall vehicle strength and passenger safety. Design engineering at Audi led to a layup comprising unidirectional and woven carbon fiber fabric reinforcements combined with a fast-cure epoxy resin system.

Further, says Diebold, Audi wanted to make some of the *R8 Spyder* composite parts using foam-cored sandwich construction, particularly in the B-pillars and the upper rear wall. Roquette says the decision to use foam core was driven by a desire to reduce »

Applying composites on a case-by-case basis

The *R8 Spyder* rear wall and B-pillars, on display at the 2017 SPE Automotive Composites Conference & Exhibition in September in Novi, MI, US. Audi evaluated 23 load cases in its effort to determine where anisotropic loads were greatest in the MSS, and then applied carbon fiber composites in those locations. Source | *CW*

the amount of carbon fiber in each structure, and, in the B-pillars, consolidate parts and increase strength and stiffness. Enhanced B-pillar performance is critical for the *Spyder*, a convertible, when the vehicle's roof is down. In a non-convertible vehicle, stability and stiffness of the chassis is provided by the floor/tunnel section and the roof frame. With a convertible, the floor/tunnel section must provide all of the stability and stiffness.

Audi wanted a foam core surrounded by carbon fiber infused with epoxy via resin transfer molding (RTM). The main problem with this plan, Diebold recalls, was finding an easy-to-handle core material that was neither too heavy (100-150 kg/m^3 density) nor so light that it was susceptible to crushing during the RTM process. Audi eventually settled on a novel solution and a relatively new product on the market, a polymethacrylimide (PMI)-based foam. "It compacts globally, is not easily crushed and is easy to handle," says Diebold. "Other core materials were tried, but the problem of heat, cost or some other limitation did not make it possible." He adds that the foam can be molded to almost any three-dimensional shape, allows for the integration of bosses, inserts and other metallic parts, and obviates the need for the machining and milling typically associated with foam core fabrication for composite structures. Further, Diebold describes the PMI as having a homogenous cell structure that is amenable to hydrostatic testing.

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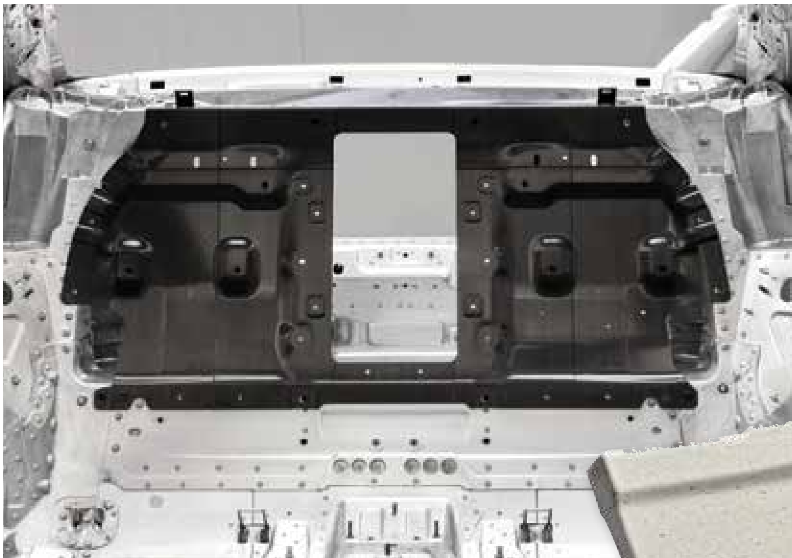
Read this article online | short.compositesworld.com/AudiR8Wall

Read more online about autocomposites manufacturing in *CW*'s "Plant Tour: BENTELER SGL, Ort im Innkreis, Austria" | short.compositesworld.com/BentelerSG

A new type of RTM

The final piece of the developmental puzzle was the refinement of the RTM process that would bring the materials together. This was not trivial because what Audi developed would, eventually, be handed off to a tier supplier for production.

Although high-pressure RTM (HP-RTM) has become a favorite of autocomposites manufacturers, and Roquette says Audi considered it, its 120-bar injection pressure — with even higher pressure at the injection point — posed a threat to the integrity of the foam cores, the use of which was not going to be compromised. This drove Audi to look for a way to reduce injection pressure without increasing cycle time. The task seemed impossible until Audi connected with researchers who were doing work with mold cavity pressure sensors



Expanding the MSS concept to other models

The new Audi *A8* luxury-class vehicle features a slightly modified composite rear wall, pictured here. Audi is avidly working toward material and processing technologies that will help it get such parts into high-rate production. Source | Audi

Double protection against core crush

To reduce carbon fiber use yet meet strength and stiffness requirements for the rear wall, B-pillars and tunnel, Audi went with a sandwich structure that incorporated moldable polymethacrylimide (PMI) foam core billed by the source as crush-resistant. Audi nevertheless developed a low-pressure resin transfer molding process for part fabrication to avoid the risk of core crush. Source | Evonik

to fine-tune the interaction of injection pressure, compression force and mold gap in RTM to optimize that molding process.

Roquette says Audi's research, in conjunction with the researchers, revealed that if cavity pressure was the governing and primary variable during the molding process, then mold gap height and press force could be moderated and adjusted to produce a cycle as fast — if not faster — than HP-RTM provides. Audi calls its process ultra-RTM. For the *R8 Spyder* sandwich structures, injection pressure does not exceed 40 bar, mold gap opens to as much as 0.6 mm, press force maxes out at 500 MT and mold temperature does not exceed 123°C. With this new process, the injection time can be reduced to 15 seconds and the overall cycle time to less than 5 minutes. This also means parts can be made on a smaller, less-expensive press, using less energy, and without risking the integrity of cores.

Future developments

Roquette says that when Audi first set out to manufacture composite parts for the MSS, the strategy was to employ European autocomposites fabricators who might have the capacity and expertise to efficiently and quickly design and make the parts the OEM required. Ultimately, however, Audi decided that such composite materials and processing expertise should be developed in-house first.

"What we learned is that if we really want breakthrough technologies in a field like composites, then we have to understand it on our own, and we have to develop it on our own," Roquette says. "We have a huge team, and we were just very focused on this project, every day."

When it came time to transfer the material and processes Audi developed for the *R8* to its two European automotive composites suppliers, which would do the actual manufacturing, there was some uncertainty: "This is not technology we could have bought on the open market," Roquette says. "So, when we approach our suppliers, who have manufactured composites for a very long time, it is very different for them to accept this new technology. And we did give them this technology and showed them how to use it, but in the end, making good parts is up to the supplier, so they are taking a great risk. In this way, it is not easy being a supplier to an automotive OEM."

Lessons learned did not end with the 2016 R8 *Spyder*. In 2017, Audi introduced its four-seat, luxury-class *A8*, with a carbon fiber composite rear wall and upper rear shelf, both made via ultra-RTM. As to higher volumes, there is still work to do, says Roquette: "The cost of a finished carbon fiber part is still too high. Now we are on a level where we have to look at every point. It is not just the fiber price, it's not just the speed of RTM. It's *everything*. Resin price, adhesive price, the whole chain. We must use new ideas." CW

ABOUT THE AUTHOR

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