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Composites Inspection: BIG BLADES, BIG BUSINESS

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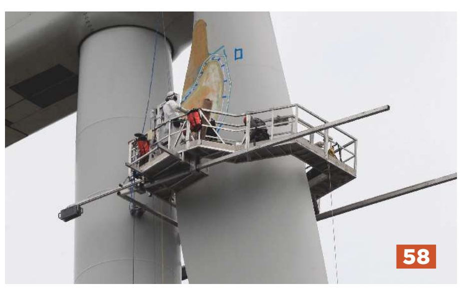
COLUMNS



DEPARTMENTS

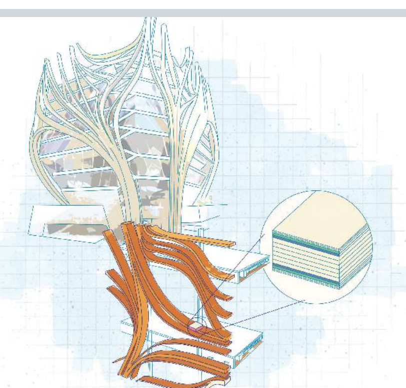
FEATURES

ON THE COVER

As pioneering wind farms near their quarter century mark, wind blade inspection has become big business. Inspection methods and technologies vary widely, and *CW* covers the range and talks to key practitioners in this issue on p. 58. Here, workers perform repairs from self-adhering scaffolding to damaged areas on blades discovered by inspectors who viewed the blades while suspended by ropes and harnesses.

Source / Rope Partner

FOCUS ON DESIGN



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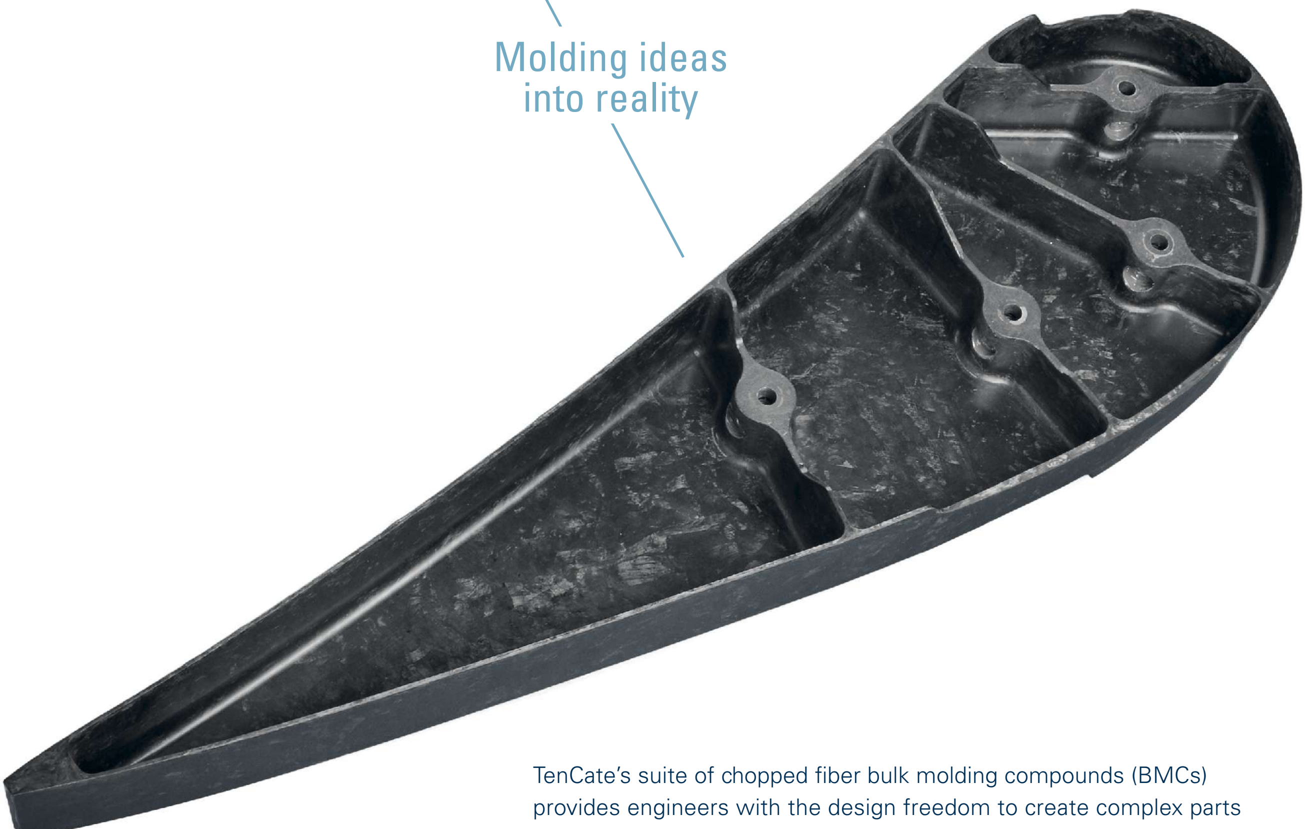

When worlds collide — literally

» In the 1990s American TV comedy "Seinfeld," there was an episode in which George lived in two worlds. One was represented by his friendships with Jerry, Elaine and Kramer, the other by his relationship with Susan, his fiance. George wanted these worlds kept separate, so that the "sanctuary" of his friendships would not be contaminated by his romantic life, and vice-versa. When Elaine and Susan began spending time together, and then Susan took George's seat at his favorite diner, George famously exclaimed, "My worlds are colliding!" Comedic chaos ensued.

I am reminded of colliding worlds as I write this. I joined *CompositesWorld* as editor in 2006, after a decade as editor and then publisher of *Injection Molding*, a trade publication that, as the name implies, served the injection molding industry. I came to my new job at *CW* expecting *some* overlap of materials and technology. Instead, I found two separate worlds.

Injection molding was already a mature manufacturing process: highly automated, machine-dependent, volume-driven and cycle time-focused. Part quality derived primarily from good process control, verified by random inspection. Resins were almost exclusively thermoplastic and most of the time were unreinforced. Technological innovation, by 2006, had slowed and was incremental at best. Major end-markets were the automotive, medical, packaging, appliance and consumer-goods industries. Aerospace, marine and wind energy — the mainstays of the composites industry — were almost never mentioned in *Injection Molding*.

In the composites world, I discovered a landscape of resins, fibers, fiber formats, tools and manufacturing processes with the potential for nearly infinite variation, where hand work was (and still is) not uncommon, and where there was little dependence on machinery of the type familiar to the injection molding industry. Cycle times were measured in hours, or at best, minutes, not seconds. Quality for many parts was assured via 100% inspection, and quality assurance via process control was nearly unheard of. The great variety of available materials and processes made composites highly susceptible to change and innovation. Aerospace, marine and wind energy dominated. Automotive composites were relegated to the likes of Chevy's *Corvette* and Lamborghini's *Aventador*.

Of course, much has changed since 2006. Dynamic innovation, still a major driver of industry growth, has pushed composites into applications difficult to imagine 12 years ago — most notably, into mid- to high-volume automotive manufacturing. Driven by forces that we have covered in *CW* — fuel efficiency regulations, emissions regulations, e-vehicle lightweighting — it's facilitated by faster-curing resins, cheaper carbon fiber and more efficient processing.

And this is where my worlds collide. A fast-emerging process is combining the endless potentialities of continuous fiber reinforcement from my present reality with the mature and established injection molding process. But unlike in George's universe, chaos isn't the result. In fact, it's cause for celebration: Called *overmolding*, it enables the fabrication of *selectively reinforced* parts. Continuous fiber preforms are placed strategically in a mold cavity and then are overmolded, partially or completely, by unfilled or chopped fiber-reinforced thermoplastic. This process is appealing for several reasons, but primarily because it offers molders the opportunity to produce structural parts with engineered reinforcement *only where needed* and produce those parts at unprecedented high rates. The result is a high quality, but much more economical, process and part, which is good not only for the automotive sector, but the aerospace industry and other end-markets as well. Not limited to injection only, overmolding via compression processes also is possible.

For these reasons, *CW* is proudly hosting the Composites Overmolding conference, June 13-14, in Novi, MI, US. Speakers and presentations will explore the companies, materials and processes that are shaping overmolding today. The slate of presenters will include representatives from Ford Motor Co., Fraunhofer, PolyOne, SABIC, SGL, Victrex, KraussMaffei, Arburg and RocTool. Visit **compositesovermolding.com** for more information. I will of course be there, watching my worlds collide. I hope to see you as well.

JEFF SLOAN — Editor-In-Chief

Support: Seek, ask and find

» My career in the composites industry started in my early days as a surfer, when I received all kinds of help and support from other surfers, who showed me and then taught me composite repairs. Heck, making repairs to my surfboard in the early 1970s was as complex for me, then, as carbon fiber thermoplastics are today for most of us. I had no clue what to do back then, much less any money to have someone fix the catastrophes I created as I learned. You know — lots of splash and burns.

The people who helped me so long ago inspired me to do the same in my career. And I've always known that if I needed help, I could ask and get the answers I needed, from sales reps, manufacturing reps and friends I have made over many years. They will all help if you just ask. Having spent 40+ years working with composites, I've made my share of mistakes. Sometimes I've encountered what seemed like endless challenges on projects. "Live and learn," they say. And, learn I did. Everything about composites has changed since those early days. But, some things will never change. Composites people are among the most innovative and forward-thinking people on our planet.

> The people who helped me so long ago inspired me to do the same in my composites career.

Technical support: It's there to be used

In today's fast-paced process development and material enhancements environment, technical support is a necessary part of today's composites world! We have small to very large companies working, relentlessly, to master the next, best processes and materials. Ever-increasing pressure for faster curing, lighter weight and, dare I say, "cheaper," components and processes seem to be the current buzz.

Having been exclusively in a technical support role during the past four years, I have worked with clients all over the globe to help them meet their goals. There are some notable scenarios that seem to be common. In almost every instance, the client has made an attempt — if not several attempts — to integrate new materials *before* reaching out to tech support for help. Or, in many cases, clients have just given up, licked their wounds and then gone back to the previous composites or the legacy materials they were using.

Failed attempts and outright surrenders *aren't* necessary. Remember: things are changing every day. Keeping up with it all is almost impossible. There are no bad questions. For every new enhancement for composites, there are people ready and *willing* to help.

Material suppliers, distributors and materials manufacturers recognize that technical support is necessary. Most have worked hard to build teams of support professionals specifically tasked to help processors make technology transitions less painful.

I am confounded at how infrequently these fantastic resources are used. In some of the most challenging processes, even at companies recognized for highly advanced composites parts, I have found that with the integration of a new material — be it soft goods or resin systems — some of the most basic things are overlooked by some of the most highly skilled people. Simply making changes to materials and using the same processing usually does not work. Sadly, the blame is almost always placed on the new materials.

Reaching out for the right support

But when looking at any change, it's critical that whoever you reach out to for support has a clear understanding of your product, your current processing capabilities, your goals and the quality issues you currently deal with *before* you initiate trials.

An example I know of concerned the fabrication of bladder-molded parts with surface quality issues. In this case, a consultant was called to help integrate a new process and new materials to produce a lighter, tougher, more impact-resistant product, but he was unable to get an acceptable surface finish. Before the project was abandoned, I was called in, and a simple adjustment in processing — "a couple pressure bumps" — enhanced the surface quality and the new material was then integrated with perfect results. Addressing everything before the integration of new material helps to make the transition.

Remember, when things are changing, that means "all things" in some cases. These new materials have been proven to be successful *when deployed properly!* So, contact each manufacturer and ask specific questions. If you are not satisfied, ask for another opinion! Each supplier in your process chain has people skilled and ready to help you succeed. Use them.

Support is the key to today's composites industry growth and health. Many of us have been around long enough to know we don't know everything. We've also been around long enough to have made and learned from many mistakes. So, let's train our enthusiastic and innovative youth to ask before they leap, too! CW

ABOUT THE AUTHOR

Russ Emanis has been the chief composites engineer for Innegra Technologies (Greenville, SC, US) since April 2014. He has more than 30 years of composites and processing experience. Before coming to Innegra, Emanis was previously employed at JB Martin and at aerospace firm Lockheed Martin.

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Composites: A neophyte's quandary

» This month's column comes on the heels of my return from Europe, where I visited JEC World in Paris and made visits elsewhere. Once again, I saw continued progress toward a more ubiquitous future for composites, and I made some general observations about what *some* of that future might look like. But that and a meeting I had along the way led me to ponder a hurdle we still need to conquer, one that has wide-reaching implications. First, the things that stood out to me:

There could be a place for composites in e-mobility. Frankly, I've had some doubts about what role composites might play in the world of electric, and especially, *autonomous* electric vehicles. With the cost of batteries dropping at a rapid pace, how much will vehicle mass matter, especially for ride-sharing/local routes where *range* is less of an issue? Will a metallic spaceframe with "snap on," low-modulus neat plastic body panels achieve the styling objectives of driverless vehicles? There don't seem to be clear answers. Nonetheless, I saw several examples in Paris, albeit prototypes, of integrated structural battery boxes doubling as skateboard-like chassis elements. The battery enclosure, if nothing else, appears to be a logical composites application.

It's time we consider ways that we can hang out those signs that say: "New to composites? Start here."

Automation is making a difference. Last year, numerous manufacturers were showing off machines that *could* automate layup and downstream processing. This year, Voith Composites showed a fully automated layup, infusion, trim and assembly cell for the Audi *A8*'s carbon fiber back panel and package shelf that is in *production*. This didn't happen overnight — Voith and Audi announced their partnership back in 2011. Such transformative technologies take time to mature.

Hybrid structures are gaining traction. Although most are still patches of continuous fiber thermoplastics (UD tape or woven organosheet) overmolded with short fiber thermoplastics of the same polymer family, the most highly structural examples I saw were *thermoset* — continuous carbon fiber prepreg inserts overmolded with high-load carbon fiber sheet molding compound (SMC). Clearly, these hybrid technologies help address waste and cost. The challenge here is designing and modeling the structural performance because no one single code has been developed yet to address this mix of materials, either in thermoplastic or thermoset.

It was as I observed and interpreted technological possibilities that I met with a major industry supplier, who offered up this provocative question: "If you showed up at this event without any understanding of composites, how would you find your way around?"

That still has me thinking. Most who attend JEC have a grasp of polymer composite basics and many have considerable experience or expertise in one or more composites applications. We come looking for, and can recognize, the new and novel and can discern the impact it might have. If you're a new hire at an aerospace or automotive firm, chances are there are those who have preceded you who have at least a basic understanding of composites and can point you in a few directions. But say you're a civil engineer, trained in concrete bridge construction, and your boss sends you to the world's largest composites exhibition to learn about this new technology called "composites" he's been reading about? Or you work for a utility company where local infrastructure has been ravaged by a hurricane and have heard that composites can help "harden the grid," but you only know wooden poles and metallic transmission towers? Or you now make a product from wood, metal or plastic, but you're "looking into" FRP? What then?

An oft-cited concern is that new engineers are not exposed to composites as part of their materials science courses. Another is that the public at large has little understanding — or appreciation — of the ways composites can make products more functional, stylish and longer lasting. No simple solutions there. But for trade shows? How about this: When you visit an art gallery or major museum, you are often greeted by a *docent*, typically a volunteer, who is well versed in the items on display and who offers to help you appreciate their significance, putting into context the exceptional creations or findings among the treasures there. Perhaps JEC, CAMX and other large composites trade shows should consider hanging a large sign at the entrance that says "New to composites? Start here," with an arrow pointing to an information desk staffed with "old hands" that have been around the industry a while. I know that I, and many others, would be glad to mentor such neophytes for an hour or so as they start their discovery of the composites universe. Chances are, *we* will learn something as well. 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 also is the 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 has 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.


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Composites Index finishes best quarter on record

March 2018 – 59.9

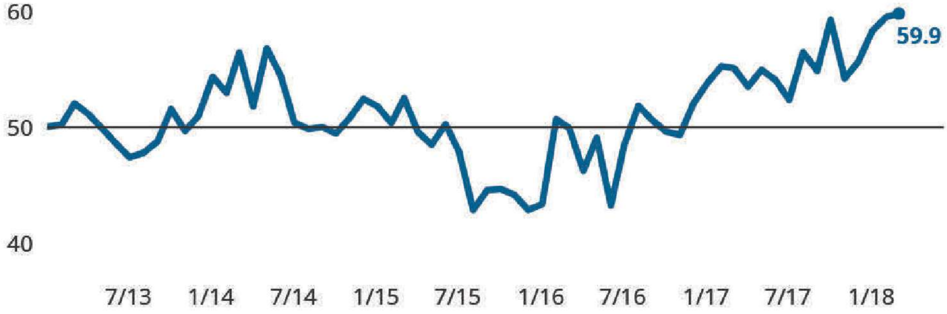
» The GBI: Composites Fabricating index closed March by setting both a monthly and a quarterly record high of 59.9 and 59.3, respectively. Compared to the same month one year ago, the Index increased approximately 8.2%. A review of the underlying data for the month by the Gardner Intelligence team indicates that the New Orders, Production, Supplier Deliveries and Employment subindices lifted the Composites Fabricating Index — an averages-based calculation — higher, while Backlogs and Exports pulled the Index lower. With the exception of Exports, all other Index components showed expansion (readings of >50.0) in March.

Although Production and New Orders have been the predominant drivers of the Composites Index over the past 18 months, readings of Employment and Supplier Deliveries both experienced strong growth in March, pushing the overall Index into record territory. The growth in Backlogs, despite fabricators' efforts to increase Production and, more recently, Supplier Deliveries, suggests that 2018 is likely to be one of the best years since the Index was first recorded in 2011. 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 in a wide range of industries. Guckes received his BA in political science and economics from Kenyon College and his MBA from Ohio State University. **mguckes@gardnerweb.com**

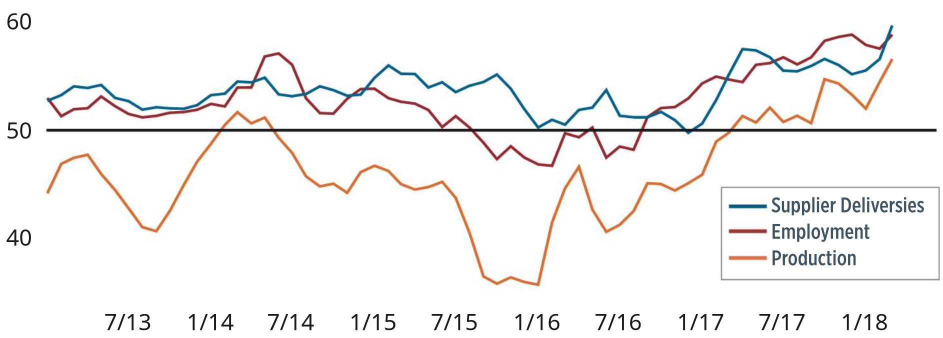
GBI: Composites Fabricating



Index driven to recordbreaking heights

The Composites Fabricating Index set consecutive record highs in February and March. Recent growth in Supplier Deliveries and Employment readings have complimented the more enduring upward trends in New Orders and Production to put the Index in record-breaking territory.

GBI: Composites Fabrication - Supplier Delivery, Employment and Backlog (3-month moving average)



First-quarter expansion extends to Backlogs

In the early months of 2018, strong expansion was observed in Employment and especially Supplier Deliveries. Although both Production and Supplier Deliveries grew quickly in the first quarter, that growth did not head off an increase in Backlogs.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Thermoplastic composites (TPCs) come on strong in the aerospace market; carbon fiber giants respond with investments in major TPC sources; SAMPE Europe's Summit summarizes tremendous growth in the advanced composites industry.

AEROSPACE

Thermoplastic composites: Past the tipping point?

The manufacturing world watched a decade ago as composites gained supremacy over aluminum in the production of commercial aircraft. Fiber-reinforced thermoset tapes, placed automatically on massive tools and cured in even larger autoclaves under significant pressure and heat, formed the wing and fuselage structures of The Boeing Co.'s (Chicago, IL, US) 787 and the Airbus (Toulouse, France) A350 XWB. These carbon fiber/epoxy primary structures resulted in genuinely revolutionary midsize, twin-aisle passenger aircraft.

And these events made composites, particularly the carbon fiber-reinforced plastic (CFRP) variety, a household word. They also signaled the industry's first big steps toward what has since been an irreversible advance toward industrialization. As a result, CFRP has grown dramatically in higher-volume, nonaerospace markets including oil and gas, automotive, industrial and consumer applications.

Thermoset composites processing has come a long way over the past 10 years. Snap-cure resins (see *CW's* report on sub-1-minute-cure epoxies, on p. 28), robotic tape placement with onboard, real-time inspection and less energy-intensive and time-consuming out-of-autoclave cure cycles, have given a variety of manufacturers viable options for low- to medium-volume series production.

Thermoplastic composites (TPCs), however, have been developed in parallel for more than two decades now, aimed at both aircraft and nonaerospace applications. Although thermoplastics, like thermosets, must be thoroughly consolidated to achieve required part surface quality and acceptable void content (<2% in aerospace), they do not crosslink, and therefore, offer abbreviated cycle times. They also are inherently fatigue-resistant (addressing a key concern for aircraft manufacturers) and provide toughness, durability and straightforward recyclability, something not so straightforward for thermoset composites.

It makes sense, then, that automated placement, unidirectional (UD) tape and thermoplastics have recently converged. But the momentum it has gained is a bit breathtaking: In *CW's* 2017 print article and Blog series on automated preforming, as well as its two-part 2018 series on in-situ consolidation of TPCs, the potential for placement, consolidation and real-time inspection of thermoplastic composite tapes in a single step, without subsequent application of heat and pressure via autoclave or other means, is within reach.

The savings in time, capital and operating expenses that these TPC developments represent is impossible to ignore. Indeed, for its recent TPC coverage, *CW* has been in contact with no less than 18 companies that offer automated tape placement technology: Accudyne, AFPT, Automated Dynamics, Automation Steeg and Hoffmeyer, Broetje, Cevotec, Composite Alliance Corp., Compositence, Coriolis Composites, Dieffenbacher, Fill, Mikrosam, MTorres, Novotech, Tri-Mack Plastics, Van Wees UD and Crossply Technology, Voith Composites and the Quilted Stratum Process (QSP) at Cetim. This list is by no means exhaustive. Others are doing the same and still others are focused on overmolding of tailored tape blanks, which is a purely TPC process. (Discover more about this developing technology at *CW's* upcoming conference "Composites Overmolding: A 1-minute cycle time initiative," June 13-14, 2018. Learn more at short.compositesworld.com/1minute.) Notably, a once fragmented supply chain is now coming together into a more integrated, streamlined whole, offering truly industrial capacity in both aerospace and nonaerospace markets. *CW* reports on two key examples of TPC potential that are already bearing fruit, on pp. 20 and 26.

Exactly one year ago, *CW* sat down with Tim Herr, aerospace director at Victrex (Thornton-Cleveleys, UK) and Tom Kneath, director of sales and marketing for Tri-Mack Plastics Mfg. Corp. (Bristol, RI, US), to discuss the formation of TxV Aero Composites. "Thermoplastic composites has been 'the next big thing' for 30 years," said Herr. The drive to abbreviate part production cycles has come full circle. "More recently," he pointed out, "the commercial aerospace market has signaled that thermoplastic composites are the material of the future that will enable them to achieve necessary cost reduction via highly automated production systems. Manufacturers have made it clear to us that their throughput rate must be higher than it is today."

It is no mere coincidence that Hexcel (Stamford, CT, US), the principal supplier of carbon fiber to Airbus for its commercial aircraft, partnered with thermoplastics source Arkema (Columbes, France) a mere two weeks after Toray Industries (Tokyo, Japan), the carbon fiber source for Boeing, announced its impending acquisition of multinational thermoplastics giant TenCate Advanced Composites (Morgan Hill, CA, US and Nijverdal, The Netherlands). This follows earlier 2018 press releases from Daher (Marseille, France) and LMI Aerospace (St. Louis, MO, US) touting multi-year contracts with Boeing for thermoplastic composite parts.

Those optimistic projections for TPCs could actually prove justified, given the swell generated by automotive and other nonaerospace markets coinciding with the wave beginning to crest in commercial aircraft. Should be an interesting ride.

AEROSPACE

Virgin Galactic's *VSS Unity* successfully completes first flight


Source | Virgin Galactic

Virgin Galactic (Las Cruces, NM, US) reported April 5 that the carbon fiber composite *SpaceShipTwo*, dubbed *VSS Unity*, safely and successfully completed its first supersonic, rocket-powered flight. After two years of extensive ground and atmospheric testing, the passing of this milestone marks the start of the final portion of *Unity's* flight test program.

The flight was also significant for Virgin Galactic's Mojave-based, sister manufacturing organization, The Spaceship Co. (Mojave, CA, US). *(continued on p. 14)*

(continued from p. 13)

Unity is the first vehicle to be built from scratch for Virgin Galactic by The Spaceship Co.'s team of aerospace engineers and technicians.

VSS Unity reportedly benefits from all the data and lessons gathered from the test program of her predecessor vehicle, *VSS Enterprise*, which unfortunately was destroyed during a 2014 test flight that also killed a test pilot.

VSS Unity's flight was piloted by Mark "Forger" Stucky and Dave Mackay. The craft took off attached to the *WhiteKnightTwo* carrier aircraft, now known as *VMS Eve*, piloted by Mike Masucci and Nicola Pecile.

The mated vehicles climbed to a launch altitude of around 46,500 ft/14,175m over the Sierra Nevada Mountains and executed a clean release of *Unity*. *Unity* accelerated to Mach 1.87 during 30 seconds of rocket burn in an 80° climb. On rocket shutdown, *Unity* continued an upwards coast to an apogee of 84,271 ft/25,686m before readying for the downward return. At this stage, the vehicle's tail booms were raised to a 60° angle to the fuselage, into the "feathered'" configuration. This design feature, which is key to a reliable and repeatable re-entry capability for a winged vehicle, incorporates additional safety mechanisms adopted after the 2014 *VSS Enterprise* test flight accident. At around 50,000 ft/15,240m, the tail-booms were lowered again and *Unity* glided home to a smooth runway landing.

The flight generated valuable data on flight, motor and vehicle performance for Virgin Galactic and marks a key moment for the test flight program.

Magnum Venus Products, ORNL install first commercially available large-format thermoset 3D printer

Magnum Venus Products (MVP, Knoxville, TN, US), announced April 13 that in partnership with Oak Ridge National Laboratory (ORNL, Oak Ridge, TN, US), the company has installed the first commercially available medium/large-scale thermoset 3D printer at the Department of Energy's Manufacturing Demonstration Facility at ORNL.

Although small-format 3D printers have been around for years, a cost-effective solution that could print large structures, and molds in particular, has been a big need and a relatively recent development. For that reason, MVP engaged with ORNL to create a 3D printer capable of printing large-scale thermoset components, which MVP could make available to its customers.

"Thanks to this innovation, research and development managers will be able to prototype faster and bring products to market faster," says Bob Vanderhoff, president and CEO Magnum Venus Products. "Procurement departments will also enjoy shortened lead time on crucial molds, allowing for rapid deployment."

"We're pleased to collaborate with MVP on this state-of-the-art printer and look forward to seeing the technology continue to progress and positively impact the additive manufacturing industry," says Moe Khaleel, ORNL's associate laboratory director for Energy and Environmental Sciences. "This collaboration is important for accelerating the pace with which new technologies can be successfully commercialized, leading to a larger range of applications and performance criteria for additively manufactured components ...."

The system features a roll-in/roll-out bed that reportedly dramatically increases the machine's productivity. The configuration allows the use of two print beds, enabling the printer to build a part on one bed while pre- and post-processing operations are performed on the other print bed offline.

Specifications include:

- Multi-axis print head and coordinated control of other print process parameters.
- Build volume: 4.9m by 2.5m by 107 cm.
- Print speed of up to 1.27m/sec (depending on material used).
- Deposition rate ≥4.54 kg/hr.
- Resolution of ≤6 mm (larger resolution is possible).
- Build platform with 454-kg capacity.
- Repeatability: ±0.005 inch (±0.1 mm).
- Large footprint easily scaled to multiple sizes

The ORNL's Manufacturing Demonstration Facility is supported by the US Department of Energy's (DoE) Office of Energy Efficiency and Renewable Energy's Advanced Manufacturing Office (AMO). The AMO supports early-stage research to advance innovation in US manufacturing and promote American economic growth and energy security.

SAMPE Europe's Summit 18 Conference

SAMPE Europe (Beauchamp, France) staged a successful and well-attended gathering, dubbed Summit 18, at the Pullman Hotel Paris Tour Eiffel on March 5, the Monday before JEC World 2018. Following a welcome by Prof. Jyrki Vuorinen, SAMPE Europe's president, the keynote address for the opening session on Automation and Manufacturing was given by Avner Ben-Bassat, president and CEO of Plataine (Waltham, MA, US). He spoke on the topics of artificial intelligence, the Industrial Internet of Things and the journey to the digital factory. A key takeaway was the concept of a *human:machine team* — the human is relieved of tedious and mundane tasks, while the machine, or digital assistant, becomes more intelligent by learning and mastering those tasks.

Ben Halford, CEO of Surface Generation Ltd. (Oakham, Rutland, UK) spoke about the need for composites to meet three goals: 1) stop making "black metal," 2) start speeding up production and 3) expand the markets in which composites can be applied. He pointed to other industries where millions of articles are made each day, with 100% quality, and challenged the audience to strive for higher yields, and greatly reduced scrap, at much faster speeds. Toward that end, Halford claimed that his company's PtFS (Production to Functional Specifications) technology can reduce cycle time by an order of magnitude though selective, controlled application of heat and pressure.

JEC Group's media director and editor-in-chief Frédéric Reux presented a comprehensive market report on composites, citing a worldwide market volume in 2016 of 11 million MT, with a value of US$82 billion. Asia represented roughly 50% of that market, and in his view, will be the fastest growing region going forward, at 6.5% compound annual growth rate (CAGR) through 2019. He cautioned, however, that "composites should have an industry-wide organization, like steel and aluminum have, to help grow our reach, going forward."

The day's second session, Materials and Processes, was anchored by keynoter Dr. Christian Weimer of Airbus Germany (Hamburg), general manager, materials and head of the Airbus R&D arm called Materials X. He addressed the issue of materials and process technologies as key enablers for aerospace innovation, and spoke about the new Airbus concepts: the *E-Fan X*, a hybrid-electric aircraft demonstrator, and the *Vahana*, an autonomous air taxi.

Next, Dr. Fabrizio Scarpa, professor of smart materials and structures at the University of Bristol (Bristol, UK), reviewed the wide range of materials that are changeable in response to temperature, pH, magnetic fields, electrical current, stress fields, light and more. The global market for these smart polymers and composites, he claims, was about US$28 billion in 2013, and that figure has since grown at a 12.5% annual rate.

NONA Composites (Dayton, OH, US) president Ben Dietsch spoke about that company's "no oven, no autoclave" philosophy, which eschews prepreg for dry materials, with a cost reportedly 50% lower than that of prepreg. Says Dietsch, "20-30% of recurring part costs comes from material cost, and 10-15% of recurring costs involves curing costs, and autoclaves are costly." Barriers to greater adoption of infusion methods, such as resin transfer molding (RTM), include the fact that many infusion resin systems are not qualified, or unavailable with tougheners, and RTM tooling costs can be high.

Professor Werner Sobek, founder of the Werner Sobek Group GmbH (Stuttgart, Germany) and head of the ILEK (Institut für Leichtbau Entwerfen und Konstruieren) at the University of Stuttgart, spoke of "build for more, using less." He gave attendees a glimpse of architectural trends — in particular, the use of thin concrete shells, where "dead weight becomes a non-issue," thanks to avoidance of overdesign.

Ramiro Gonzalez, the operations manager at Carbures Civil Works (Madrid, Spain), together with Santiago Perez-Castillo of Saertex (Saerbeck, Germany), described the process by which the "Pavilion of Inspirations" at the Norman Foster Foundation headquarters in Madrid was designed and constructed, in particular, its composite roof. Read more about this project online in the *CW* News article titled "Composite roof built by Carbures" | **short.compositesworld.com/CarbuRoof.** *(continued on p. 18)*

(continued from p. 16)

Next up was Torben Jacobsen, senior director of manufacturing and production at LM Wind Power (Lunderskov, Denmark), who spoke of the challenges of building an 88.4m wind turbine blade, including manufacturing the very thick root section, managing cycle time/cure time and dealing with the impact of the blade's enormous weight on transport: "Just the bagging film, alone, is a huge challenge." For the future, he says that the company will begin to use more carbon fiber and more thermoplastic materials, along with more optimized parts that will employ rib structures.

Jean Luc Macret, the senior manager of research and technology at ARIANE Group (Courcouronnes, France), told attendees the outlook for the company's space vehicles is that by 2020, they will be 60% composite, including the *ARIANE 6's* filament-wound solid rocket booster at 11.7m long and 3.1m in diameter.

Dr. Christian Sauer, the senior director for commercial and business development at Lufthansa Technik (Hamburg, Germany) took the stage to discuss the issue of repairing composite aircraft structure. He described a milling robot that can be attached to a plane to safely mill a repair scarf area — a 2-ft/0.61m diameter repair can reportedly be done in 2 minutes with the robotic solution.

The final speaker was Tia Benson-Tolle, the director of materials and fabrication at The Boeing Co. (Chicago, IL, US). Her presentation, titled "Challenges and Applications for Materials and Fabrication," focused on four areas where capabilities can be improved: aircraft systems, engines, materials and aerodynamics. "Materials systems are very complex today, and can be, for example, bio-mimetic, nano-tailored, virtually designed and more," said Benson-Tolle. "The future is no longer defined by one type of material," she added, emphasizing the increasing importance of manufacturability, and the increasing need for data analytics and design tools.

The afternoon ended with a panel discussion, led by Arnt Offringa of GKN Aerospace Fokker Aerostructures (Papendrecht, Netherlands), with the speakers taking questions from the audience. After closing remarks by Vuorinen, the day concluded with a networking dinner at the Pullman's Roof Top Restaurant.

SAMPE Europe's next event will be the SAMPE Conference 18 Southampton, Sept. 11-13, 2018, at the Hilton Ageas Bowl in Southhampton, UK. Read more about the event online | **short.compositesworld.com/SAMPE-EC18**.

Covestro, world's largest appliance manufacturer, sets CFRTP sights on world

Unveiled on March 8 this year, at the China Household Electrical Appliances and Consumer Electronics Fair (AWE, Shanghai), Haier's (Qingdao, China) "smart" Tianxi air conditioner is the world's first AC unit to feature continuous fiber-reinforced thermoplastic (CFRTP) materials.

The unveiling was significant for the CFRTP materials supplier Covestro (Leverkeusen, Germany; Pittsburgh, PA, US; Shanghai, China). And the relationship that has developed between them holds much promise for both. Haier is the world's number one appliance manufacturer. Products in its high-end Casarte product line ("Casa," Italian for home and "Arte" for art) already can be found in 1 *million* households.

The Tianxi conditioner is part of Haier's Casarte, line which also includes refrigerators, washing machines, water heaters and many other appliances. "Smart" air conditioners, however, are a high-growth, strategic market. The Tianxi stands at 1.8m tall and uses CFRTP in its twin-cylinder housing. Developed in partnership with Covestro, the composite material combines unidirectional glass or carbon fiber with polycarbonate (PC) thermoplastic resin in thin tapes. These are cut and stacked to form tailored laminates and then are thermoformed with existing tools at high yield rates and short cycle times, according to Michael Schmidt, co-CEO, with David Hartmann, of Covestro CFRTP.

"Up until now, we have been quite limited in terms of material selection, typically relying on metal to provide the performance and aesthetics that we require," says Shao Qingru, one of the color, material, finish (CMF) designers on Haier's Casarte design team. "CFRTP is a very attractive material for us in that it has a natural, unidirectional surface pattern right from the start, unlike metals, such as aluminum, that requires some combination of finishing processes, like sandblasting, brushing and anodizing, before it is ready to go into the product. For CFRTP, the finish is all natural and has a beauty to itself."

"Unlike metal, CFRTP is light; unlike plastics, it's stiff; and unlike thermosets, it's fast [in cycle times]," says Covestro material scientist Yilan Li, who help develop the CFRTP used in the Tianxi housing. She adds that the material is easily formed, offers design flexibility and has high temperature- and impact-resistance as well as good strength properties.

The housing is molded by Suzhou Yichangtai Plastic Co. Ltd. (Sozhou, China), which has been in the plastics processing industry for more two decades. Its general manager, Chen Jinming, says, "I see huge potential for unidirectional carbon fiber composites. UD allows designers and engineers the basic ability to tune the material to perform differently based on fiber orientation. As a thermoplastic material, it shortens cycle times and reduces costs compared to thermosets." He adds, "I think the time for thermoplastics has come. Whoever invests in the technologies now will have a competitive advantage in the future."

As is proving true elsewhere in the TPC universe, the CFRTP supply chain here is being engineered to perform as effectively as possible, led by the materials supplier with help from the key partners. Further, plans are afoot to expand the supply chain's reach in that universe: Covestro and Haier signed a strategic agreement in October 2017 to expand the scale of their partnership. The aim? Continuously develop advanced products featuring the latest materials to address the demands of the *global* home appliances market.

"As a raw material supplier, we don't just sell our materials and sit back and watch," says Covestro's Yilan. "To bring a new class of material to the market, we need to get the value chain to adopt it. If the value chain is not there, we build it."

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

Terrafugia to create new US-based jobs
The company predicts that a large portion of the expected growth will help them bring the first practical flying car to market.
04/16/18 | short.compositesworld.com/TerraJobs

Lamborghini Squadra Corse partners with HP Composites
HP will provide for engineering services and tooling as well as equipment and components for Lamborghini's competition cars.
04/16/18 | short.compositesworld.com/LamboHP

Airbus A320neo upgrades on hold
The decision seems to be based on service needs of the current A320neo fleet as well as plans to increase production of narrowbody aircraft.
04/12/18 | short.compositesworld.com/A320neoHLD

Sumitomo Corp. invests in Airborne Oil & Gas
Investment strengthens partnership between the two companies to provide the oil and gas industry with thermoplastic composite pipe solutions.
04/12/18 | short.compositesworld.com/SumiOandG

AXYZ acquires WARDJet
CNC manufacturer AXYZ International adds waterjet solutions to its offering.
04/04/18 | short.compositesworld.com/AXYZWardjt

Bye Aerospace celebrates *Sun Flyer 2* first flight
The *Sun Flyer* family of aircraft will be the first FAA-certified, US-sponsored, all-electric airplanes to serve the flight-training and general-aviation markets.
04/12/18 | short.compositesworld.com/SunFlyer2

Airbus and Zodiac Aerospace partner on passenger sleeping facilities
The modules, which would fit inside the aircraft's cargo compartments, offer new opportunities for additional services to passengers.
04/11/18 | short.compositesworld.com/AZSleep

FACC rolls out aftermarket services
The aerospace firm is tapping into new business areas, including aftermarket services based on repairing, refurbishing and replacing composite aircraft parts.
04/11/18 | short.compositesworld.com/FACCafter

Vestas, EDPR combine wind, solar, turbine-coupled hybrid demonstrator
A wind and solar photovoltaic hybrid demonstrator has recently been installed at an EDPR wind farm in Cádiz, Spain.
04/02/18 | short.compositesworld.com/VestasEDPR

Magna and GACC partner to produce composite liftgates
Joint venture to supply components for global automaker's crossover vehicle.
04/03/18 | short.compositesworld.com/MGLiftgate

AEROSPACE

Hexcel, Arkema forge thermoplastic composites alliance

On March 26, 2018, principals at Hexcel (Stamford, CT, US) and Arkema (King of Prussia, PA, US) announced that they have signed a strategic alliance to develop thermoplastic composite solutions for the aerospace sector that will combine the expertise of Hexcel in carbon fiber manufacture and that of Arkema in polyetherketoneketone (PEKK) resins.

The partnership aims to develop carbon fiber-reinforced thermoplastic tapes to produce lightweight parts for future generations of aircraft. In addition to lightweighting, these new composites will provide lower cost and faster production speeds for customers in the aerospace and the space and defense sectors. As part of this partnership, a joint research and development laboratory will be established in France.

This news followed close on the heels of a similar announcement earlier in the month: Toray Industries Inc.'s (Tokyo, Japan) agreement to purchase TenCate Advanced Composites Holding BV (Morgan Hill, CA, US and Nijverdal, The Netherlands) for its thermoplastics capabilities. The deal also lent weight to widespread industry speculation that thermoplastic composites, as well as thermoset composites, would play a significant role in the aerostructures of replacements for the top two commercial aircraft OEMs' best-selling narrowbody planes (for context on this discussion, see the Trends article on p. 12).

"I am delighted to announce this partnership with Hexcel, a leading advanced composites supplier to the aerospace industry. This association fits in clearly with our strategy to develop advanced thermoplastic composite solutions from our PEKK resins and takes effect a few months before the commissioning of our new PEKK plant in the United States in Mobile, AL, scheduled for the end of 2018," stated Thierry Le Hénaff, Arkema chairman and CEO.

Nick Stanage, Hexcel's chairman and CEO, said, "We're excited to join this collaboration with Arkema to continue exploring and defining the future of carbon fiber-reinforced thermoplastics in the aerospace industry. With this opportunity and our recent acquisition of the aerospace and defense business of Oxford Performance Materials [Enfield, CT, US], Hexcel is quickly becoming an industry leader in advanced composite thermoplastic technologies."


Source | Vattenfall

ENERGY

World's most powerful wind turbine installed in Scotland's Aberdeen Bay

What is reported to be the world's most powerful single wind turbine was successfully installed on April 9. It is the first of what will be 11 turbines deployed at Vattenfall's (London, UK) ground-breaking European Offshore Wind Deployment Centre (EOWDC) in Scotland's Aberdeen Bay.

On the same day, Vattenfall officials confirmed that the turbine is one of two that have been significantly enhanced with additional internal power modes that will enable them to generate more clean energy from the EOWDC. The two turbines have each increased from 8.4-MW to 8.8-MW capacity, and the April 9 installation represented the first time an 8.8-MW model had been deployed commercially in the offshore wind industry.

Together with the nine 8.4-MW turbines the enhanced turbines will work alongside, the result will substantially boost the EOWDC's expected output to 93.2 MW. This will enable the facility to meet the equivalent of more than 70% of Aberdeen's domestic electricity demand and annually displace 134,128 MT of CO_2.

The installation came less than two weeks after the first of the EOWDC's game-changing suction bucket jacket foundations was successfully installed. Unlike other foundations, which use expensive concrete or steel supports that must extend deeply into the seabed and/or contact bedrock, suction buckets, as the name implies, resemble overturned buckets, attached to the bottoms of support structures having three or more legs. The buckets are placed on the seabed, and are driven into the sediment by suctioning seawater out of their tops to create a vacuum. Suction buckets also enable relatively easy removal. The flow of water is reversed under pressure, forcing the bucket back out of the sediment. Although the bucket foundation is used extensively in the oil and gas industry, the EOWDC is the first offshore wind project to deploy the foundations at commercial scale, and pairing them with the world's most powerful turbines represents another industry first.

Gunnar Groebler, Vattenfall's head of Business Area Wind, says, "The turbines for the EOWDC, Scotland's largest offshore wind test and demonstration facility, help secure Vattenfall's vision to be fossil fuel-free within one generation."

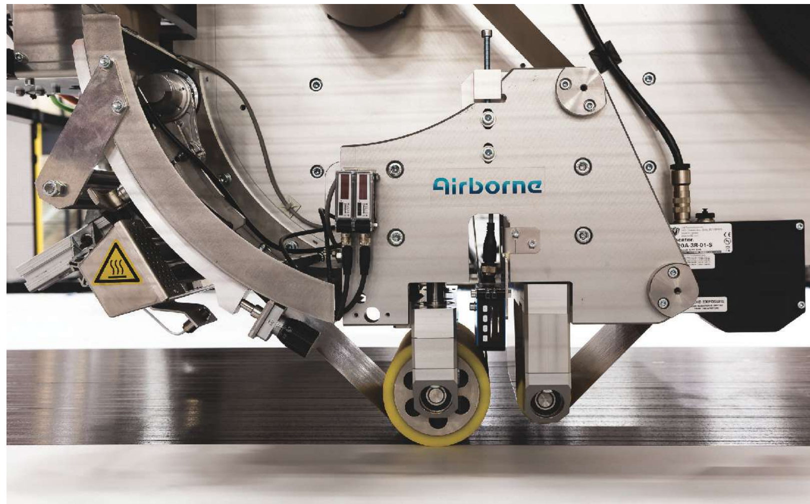
MHI Vestas (Aarhus, Denmark) has specially designed the V164-8.4 MW and V164-8.8 MW turbines which all have a tip height of 191m. Each blade is 80m long, and total rotor circumference is 164m.

EOWDC project director at Vattenfall, Adam Ezzamel, says, "The first turbine installation is a significant achievement and credit to the diligence and engineering know-how of the project team and contractors. For it to be one of the 8.8-MW models makes it an even more momentous moment because it further endorses the EOWDC as a world-class hub of offshore wind innovation.

"We are very excited by the cutting-edge technology deployed on all the turbines and it is remarkable that just one rotation of the blades can power the average UK home for a day."

MHI Vestas chief operations officer, Flemming Ougaard, says, "We are very pleased to have installed the first of 11 turbines at Aberdeen Bay. Our collaboration with Vattenfall not only provides clean wind energy for the UK, but also is an important opportunity for us to gain valuable experience with several different technologies. We look forward to the successful installation of the remaining turbines."

Jean Morrison, chair of Aberdeen Renewable Energy Group (AREG, Aberdeen, Scotland, UK), says, "The EOWDC is leading the way in terms of innovation for the offshore wind sector and will help enable the next generation of offshore wind. It's a real coup for the region to have the world's most powerful turbines on its doorstep and cements Aberdeen's position as a major global energy city. It also will lead us to a greener future."



Airborne, Siemens, SABIC partner for TPC mass production

Having acquired Fiber Reinforced Thermoplastics BV (FRT, Lelystad, The Netherlands) in 2016, SABIC (Sittard, The Netherlands and Pittsfield, MA, US) was looking for a partner to produce large quantities of thermoplastic composite (TPC) parts using FRT's trademarked UDMAX thermoplastic tapes at a radically lower cost. Airborne (The Hague, The Netherlands), answered the call. "We have been doing this type of work for a variety of industries," says Airborne founder and director Arno van Mourik, whose company is the leading manufacturer of TPC pipe for the oil and gas industry. In 2015, Airborne had teamed with Siemens PLM Software (Plano, TX, US) and KUKA Robotics (Augsburg, Germany) to pursue digitalization of composites processes and built its Digital Factory Composites Field Lab. "We have developed software and an industrialized process that now produces 40-50 [metric] tonnes of continuous product in one go, without touch labor," he claims.

Partners SABIC, Airborne and Siemens have great ambitions for the future. "The machines we are now building will attain our goal: hundreds of thousands to *millions* of parts per year," says SABIC business leader for composites Gino Francato, who adds that the future is not far off. "We are building an actual production line, which will produce parts later this year." Nor will the partners' reach be limited. Target markets include not only pipes but automobiles and commercial trucks as well as aerospace and consumer electronics.

The vision is a small number of very flexible production lines that can handle from very small to very large series-production runs *on demand.* "Process digitalization enables this reconfiguring of the line to the precise, optimized settings for each product," says Francato. Qualification in automotive and consumer electronics is not as lengthy as in aerospace, he points out, "so we can make sure we have a very robust system here, first." He adds that this partnership will accelerate the development and application of thermoplastic composites via digital processes.

John O'Connor, Siemens' director of product and market strategy, says his company has the ability to digitize and integrate intelligence throughout the process chain. Van Mourik says that will shorten development time. "We don't have to do all of the analytics by hand. These digitalized systems will help to fill in much of the data and detail." This is in direct contrast to the fragmented TPC parts value chain that has been the norm in the past. "Now we are optimizing materials and processes together to radically reduce cost and time to market," says Van Mourik.

BIZ BRIEFS

METYX Composites (Istanbul, Turkey) has completed an agreement with the Gaston County Economic Development Commission in the US state of North Carolina to acquire a manufacturing facility for its new **METYX USA** Technical Textiles Division. The 30-acre (120,000m²) site includes 130,000 ft² (12,000m²) of covered space, located in Ranlo, NC, US, a town approximately 28 miles west of Charlotte, NC, US.

METYX USA will initially focus on setting up technical textiles production lines for manufacturing a range of glass fiber and carbon fiber fabrics, along with sales, customer service and warehousing facilities, which will serve the North American composites market. Production is expected to start by the end of the third quarter, this year.

Saint-Gobain (Courbevoie, France) has acquired **HyComp** (Middleburg Heights, OH, US), a leading supplier of composite components made with proprietary carbon fibers and thermoplastics, used in the aerospace industry. HyComp is a custom injection, compression and transfer molder of engineered thermoplastics and thermoset composites into finished parts. The molder specializes in terminal blocks, mechanical components, rigid seals and composite bearings.

FAST & FASTER: Rapid-cure resins drive down cycle times

New systems include sub-1-minute cures ideal for higher auto production volumes.

By **Peggy Malnati** / Contributing Editor & **Jeff Sloan** / Editor-in-Chief

Fast Cure Thermosets for Automotive					
Supplier	Product	Name & Grade	Cure	Target Processes	Notes
Huntsman	Epoxy	Araldite® LY 3031/ Aradur® 3032	30 seconds @ 140°C	WCM or DFCM	EPT: 1 minute
Huntsman	Epoxy	Araldite® LY 3585/ Aradur® 3475	1 minute @ 140°C	WCM or DFCM	EPT: 1 minute, 30 seconds
Huntsman	Epoxy	Araldite® LY 3585/ Hardener XB 3458	2 minutes @ 140°C	WCM or DFCM	EPT: 2 minutes, 30 seconds
Hexion	Epoxy	EPIKOTE™ Resin TRAC 06000/ EPIKURE™ Curing Agent TRAC 06130	50 seconds @ 135°C	LCM/RTM	Best used with Internal Mold Release Heloxy™ Additive TRAC 06805
Hexion	Epoxy	EPIKOTE™ Resin TRAC 06170/ EPIKURE™ Curing Agent TRAC 06170	45 seconds @ 135°C	LCM/RTM	Best used with Internal Mold Release Heloxy™ Additive TRAC 06805
Hexion	Epoxy	EPIKOTE™ Resin TRAC 06150/ EPIKURE™ Curing Agent TRAC 06150	5 minutes @ 120°C	LCM/RTM	Best used with Internal Mold Release Heloxy™ Additive TRAC 06805
Solvay	Prepreg (resin not specified)	Solvalite 730	3 minutes @ 150°C 1 minute @ 170°C	Compression molding	Novel resin chemistry designed for volume production
Dow Automotive	Epoxy Prepreg	Vorafuse Epoxy P6300 prepreg	2 minutes	Compression molding	DowAksa supplies carbon fiber
Dow Automotive	Epoxy	Voraforce P5300 Epoxy	Post-injection cure, 90 seconds	RTM	Chopped carbon fiber

EPT + Estimated part production time (Preform/layup + cure + demolding)
WCM = Wet compression molding
DFCM = Dynamic fluid compression molding
LCM = Liquid compression molding
RTM = Resin transfer molding

» Ask automakers why they'd like to use more composites on passenger vehicles and most of them will list familiar attributes: low weight-to-strength or -stiffness, tooling costs at low-to-medium production volumes that are modest vs. those for metal parts, better damage tolerance (e.g., high resistance to dents and scratches), elimination of corrosion, and greater component design freedom at no additional cost. Ask them what's holding back greater uptake and they'll point to immature design tools that don't yet accurately predict the performance of anisotropic composites (leading to slow and costly redesign), to higher part costs vs. legacy materials — particularly for advanced composites — and to conversion technologies that are still too slow to keep up with the auto industry's medium-volume programs, let alone production schedules for high-volume models, which are the ultimate targets.

A decade of multidisciplinary approaches adopted by supply-chain members *have* reduced processing times — particularly for thermosets. Out-of-autoclave processes and CNC-machinery-based technologies have reduced cycle times from hours to minutes, helping make structural composites more cost-effective vs. benchmark metallic solutions. Simultaneously, resin chemistry advances have made it possible to process thermosets at the production speeds of thermoplastics and close to those of stamped steel — a necessity if composites are to play more prominent roles in future vehicle designs. It's worth noting that many of these advances are *not* the result of repurposing technologies developed for the aerospace market. Rather they were *specifically designed* for the automotive parts manufacturers' unique process and performance needs. A key example is recent work by resin formulators to reduce epoxy cure times.

"Most-proven" system

Hexion Inc. (Columbus, OH, US) spent five years developing and commercializing three grades of fast-cure epoxies for the automotive »

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production line. In fact, the company claims its technology is the market's most proven, thanks to BMW *7 Series* vehicles (from BMW AG, Munich, Germany), which feature 16 carbon fiber-reinforced composite (CFRP) parts mainly produced via liquid compression molding (LCM — also called wet pressing) or high-pressure resin transfer molding (HP-RTM), using Hexion's fast-cure epoxies. The company says it developed the resin system to match BMW's performance and production-speed requirements for both the LCM and HP-RTM processes.

The work's nexus was the twin desire among automakers for higher productivity (via faster cycle times) and excellent impregnation (regardless of part type) explains Sigrid ter Heide, Hexion's global market development manager – transportation. "This necessitated very low viscosity [20-40 cps] and a long injection window — or thermal latency — vs. cure time," she explains. "We developed these materials for liquid molding processes [e.g., LCM and RTM] and to be fiber agnostic — to work equally well with carbon or glass, continuous rovings, chopped fibers or fabrics."

Two additional, specially designed components help round out the system. The first is an internal release agent that enables an entire shift's worth of demoldings before it becomes necessary to stop and clean the tool, yet reportedly does not interfere with adhesion-sensitive postmold finishing, such as bonding or painting. The second is a multi-ingredient curing agent that helps ensure thermal latency with snap cure. "The system is really pretty well developed and balances processing attributes with excellent mechanical properties, such as toughness and high thermal resistance," notes Roman Hillermeier, Hexion's global transportation technology leader – automotive. He also cites strict control of ingredients and narrow specs that ensure excellent and consistent performance.

> Hexion claims its fast-cure epoxies are the most proven, based on their performance in BMW *7 Series* cars.

The EPIKOTE resin TRAC 06000 (EPTRAC 06000) with EPIKURE curing agent TRAC 06130 (EKTRAC 06130) is used on BMW *7 Series* parts. The more recently introduced EPTRAC 06170/EKTRAC 06170 system offers higher T_g for the same types of parts. And EPTRAC 06150/EKTRAC 06150 is preferred by tier suppliers for easier molding/demolding when processes aren't fully automated. Cure times are temperature-dependent: EPTRAC 06000/EKTRAC 06130 cures in 120 seconds at 120°C, and 50 seconds at 135°C, while EPTRAC 06170/EKTRAC 06170 is 5 seconds faster at the same temperatures (e.g., 45 seconds at 135°C).

All system components are described as Registration, Evaluation, Authorisation and Restriction of Chemicals

(REACH)-compliant. Although the resin system's T_g is technically lower than both the European and North American E-coat (electrophoretic rust-coat) systems applied to the body-in-white (BIW), Hillermeier says that so long as parts are supported (via attachment to a body structure) during E-coat or painting, no surface or dimensional changes should be seen. The system is solvent-free and, therefore, exhibits low volatile organic compound (VOC) emission, regardless of whether the resin is processed in an open or closed mold. Shelf life is comparable to standard epoxies (12 months at room temperature).

Asked if there are exotherm issues, especially with thick parts, both ter Heide and Hillermeier say, no, but add that it's unrealistic to expect sub-1-minute cures in 10-mm thick parts; however, they say, it is possible with part thicknesses of 1-5 mm. They acknowledge that problems could arise (e.g., premature cure in runners and injection ports), so the emphasis is on the importance of good tool design for any fast-reactive system. No major equipment changes are needed to run these materials other than avoiding corrosion-sensitive metals and natural rubber seals, which are vulnerable to the epoxy chemistry, and selecting faster mixing and injection rates at given temperatures. There already is substantial commercial experience running these materials on processing systems from KraussMaffei Technologies GmbH (Munich, Germany), Hennecke GmbH (Sankt Augustin, Germany) and Cannon USA Inc. (Cranberry Township, PA, US).

An even faster system

Huntsman Advanced Materials (The Woodlands, TX, US) also offers a sub-1-minute-cure epoxy system for automotive. Although one resin grade, Araldite 3031, is offered, it can be paired with one of several curatives to provide four to five different variations. The system was developed at the request of European automakers who wanted advanced composites throughput rates close to steel-stamping speeds. Depending on molding temperatures and part size, cure times reportedly can be as fast as 30 seconds at 140°C, yielding a 1-minute button-to-button molding cycle.

The materials are described as so reactive that they must be used in conjunction with injection or 2K mixing/dispensing systems, making them ideal for liquid molding processes (RTM and LCM) or Huntsman's own dynamic-fluid compression molding (DFCM) variant (see Learn More, p. 32), said to provide higher fiber-volume fractions (to 65%) than epoxy achieves in RTM, due to the vacuum applied in the mold. "Folks are comfortable with prepreg cure speeds and know-how to take advantage of those systems," notes Matt Pogue, Huntsman's market development manager. "The real trick is to bridge the gap between niche production runs of 1,500 and medium-production volumes of 30,000 to 75,000 units annually on a » single tool set. To achieve that level of productivity, you have to have a 30-second cure. Right now, industry is still trying to understand what kind of investment is required to achieve those speeds." He notes that Huntsman did a full analysis of cost/weight saved for mid- and high-volume vehicle classes. Although he acknowledges that a number of assumptions were made in the study, he also says that even at volumes above 100,000 parts/yr, advanced composite part costs are in the same range as those for reinforced polyamides. "With these numbers, we're getting a lot of interest from people who already know a bit about structural thermoplastics," adds Pogue, referring to those familiar with injection overmolding. "On top of that, we're giving them a process that fits into the cultural norms of automotive, as we're not asking them to do closed mold injection with preforms."

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Read more online about dynamic fluid compression molding (DFCM) in "Huntsman announces 60-second cycle times with compression process" | short.compositesworld.com/60secComp

The new resin system is fiber agnostic, works equally well with fine- or heavy-tow fibers and heavy fabrics, offers the year-plus shelf life of conventional epoxies and works on conventional epoxy processing equipment. That said, it is definitely designed for continuous- rather than discontinuous-fiber systems, such as SMC. The technology is no more prone to exotherm issues than RTM, and typical parts are up to 2 mm thick. Can it handle paint and E-coat temperatures? "That depends on how the part's supported [e.g., on the BIW]," says Carl Holt, Huntsman technical service manager. "We're doing studies on that now, but our focus when designing this system was to make it cure fast and be affordable, not to have a high T_g. To get those kinds of changes, you have to start giving something up somewhere."

The technology is in commercial trials and customers are reportedly pleased with the results. One advantage Huntsman says it offers to customers is in-house expertise in flow-reaction modeling, using commercial codes like PAM-RTM (ESI Group, Paris, France). "Our expertise in modeling resin reactions comes into play when we start running trials," adds Holt. "Rather than spending days figuring out pressures, temps and injection speeds, we load a customer's part design into the software and do all that work up front. Then, on the day of the trial, we go in, dial in the numbers, and within one to two tries we're consistently making good-quality parts."

Snap-cure latecomers

Solvay Composite Materials (Alpharetta, GA, US) entered the snap-cure resins market in early 2017 with the introduction of SolvaLite 730, developed for high-volume automotive applications. SolvaLite 730 is a thermoset *prepreg* comprising what the company says is novel chemistry (i.e., not based on an existing resin matrix). Designed for high-volume applications, SolvaLite 730 reportedly offers low tack, a 3-minute cure at 150°C, a 1-minute cure at 170°C and storage stability at room temperature for up to six months. The company is targeting compression molding with this material. The resin also offers low enthalpy, a T_g of 130°C, demoldability at 170°C and a reduced total cost of ownership thanks to longer tool life, ease of storage and reduced scrap rates. Carbon fiber formats offered initially are UD fabrics of 150 or 300 gm^2, made with high-strength 5K carbon fiber. Solvay also is offering a 380-gm^2, 2x2 twill, made with high-strength 12K carbon fiber.

Dow Automotive (Auburn Hills, MI, US) also introduced in 2017 its Vorafuse Epoxy P6300, a prepreg offered in conjunction with carbon fiber supplier DowAksa (Marietta, GA, US). It also is targeted toward automotive compression molding, offering a 2-minute cure and is room-temperature stable for up to 30 days. This material was originally developed for the Ford *GT* (Ford Motor Co, Dearborn MI, US) and was applied as well in an Aston Martin automotive trunk frame structure manufactured by Faurecia (Nanterre, France) via RTM, using Dow's Voraforce 5300 epoxy and chopped carbon fiber mat. Dow officials say the part has a post-injection cure time of 90 seconds.

What's next?

These new systems help position advanced composites to compete with steel and aluminum. Is it possible to squeeze even more time out of reaction chemistry? Resin suppliers say, *yes*, but note other hurdles must be overcome first. "We know what levers to pull to go even faster, but you will give something up to do that, and we haven't heard anyone say that 30-second cures are too slow," quips Pogue, adding, "That won't impact the cost of CFRP parts the way taking cost out of carbon fiber will."

"While industry is looking for ways to make advanced composites technology more cost-competitive, rather than pushing for even faster cure times, greater cost reductions will be seen with more efficient carbon fiber usage, switching to recycled materials or through scrap reduction," adds ter Heide. "In fact, the best performance may be achieved with a hybridization of technologies." CW


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■ Carbon fiber earns its place in the return-on-investment equation

As blade length continues to increase to improve wind energy harvest, carbon fiber reinforcement in spar caps has become an efficient way to reduce overall weight-to-length and increase blade stiffness to prevent tower strikes in the event of sudden wind gusts.

Source | Epsilon Composite

Wind blade spar caps: Pultruded to perfection?

Their deflection and compressive properties' cost appeal could make pultruded carbon fiber-reinforced spar caps ideal for ever-longer turbine blades.

By Michael LeGault / Contributing Writer

» Introduced to the market about five years ago, pultruded, carbon fiber-reinforced spar caps, incorporated as the reinforcing member of wind turbine rotor blades, are a byproduct of the evolution and increasing technological sophistication of the global wind energy industry. Twenty or more years ago, when the first large-scale, commercial wind-generated power came on line, wind farms comprised turbines rated at 1 MW or less with glass fiber-reinforced blades that typically ranged from 10 to 15m in length. Today, offshore, 6- to 9-MW turbines with blades 65-80m long are the norm. GE Renewable Energy recently announced a 12-GW offshore wind turbine that will use 107m-long blades.

From an engineering and generator's perspective, the rationale for longer blades and larger turbines is fairly straightforward. According to Betz's law, the extraction of power output from kinetic wind energy by a turbine is proportional to the product of the wind velocity cubed and the effective area swept by the turbine's rotor blades — $\pi(r/2)$, where r is the rotor

Pultrusion has earned a prominent place

Zoltek Corp.'s (St. Louis, MO, US) process for pultruding carbon fiber plate begins with the feed of PX 35 carbon tow from racks of spindled tow (pictured here) into a pultrusion die, where the formed fiber is infused with a thermoset resin. Vinyl ester, epoxy and polyurethane are all candidates, depending on the turbine blade building customer. Source | Zoltek Corp.

diameter — with a maximum achievable conversion efficiency of 59.3%. Generally, the longer the blades, therefore, the greater the efficiency.

Philip Schell, executive VP, carbon fiber, Zoltek Corp. (St. Louis, MO, US), says as blades get longer, the properties of deflection and stiffness become more critical in turbine blade design and performance. "The spar cap needs to be able to handle a certain predicted level of tensile and compressive loading," Schell says. He points out that in addition to being about 30% lighter than glass by volume, carbon fiber has roughly three times the tensile strength and one-and-a-half times the compressive strength of glass, noting that these approximate figures can vary slightly, depending on the types of carbon and glass fibers being compared. Wind blademaker TPI Composites' (Scottsdale, AZ, US) president Steve Nolet says that although reduced weight, an improvement »

A range of thickness and width

Zoltek's pultruded plate, 3-6 mm thick, is produced in widths ranging from 75 mm to 300 mm. The plate has a void content of less than 1% and can be specified with a fiber volume content in the range of 58-70%. Source | Zoltek Corp.

Premanufactured for variable control

A peel ply (applied during pultrusion) is removed from the plates prior to stacking them in the spar-cap tool, generating a clean, activated surface that enhances infusion and laminating. Unlike fabrics or prepreg, the properties of the plate are fixed *before* final infusion, a feature that provides wind blade manufacturers with one less variable with which to contend. Source | Zoltek Corp.

in compressive strain and a reduction in axial fatigue certainly contribute to blade useful life, the use of carbon fiber composite spars is motivated primarily by the need to "limit deflection of these super-sized *upwind* rotors that must avoid tower strikes during operation and in the environment of stochastic winds and uncertain loading."

Pultruded plate for spar cap

Zoltek, a wholly owned subsidiary of Toray Carbon Fiber (Tokyo, Japan) since 2014, supplies more than 12,000 MT of carbon fiber materials to the wind energy market per year, and is adding new capacity at its facility in Guadalajara, Mexico, this year — in part, to meet demand for new projects in the wind energy market. Its product line includes PX 35 Tow and PX 35 Unidirectional Fabric, but also includes PX 35 Prepreg and, important for the current discussion, PX 35 Pultruded Plate.

Zoltek entered the pultrusion market about four years ago at the behest of one of its customers and, according to Schell, is today one of the largest producers of carbon fiber-reinforced pultruded plate in the world.

"There's a lot of interest in pultruded carbon fiber spar caps right now," Schell reports, noting that Zoltek has related development projects in the works with many of the world's largest wind turbine manufacturers. "One of the appealing facets about carbon fiber spar caps is that it opens the door to design not only lighter, but thinner, blades with improved aerodynamic performance," he says. This feature of the materials, when fully optimized, means that the increased cost in materials can, over time, be offset by greater annual energy production (AEP) and levelized cost of energy (LCOE).

Zoltek pultrudes plate at its US manufacturing plant, and at facilities in Hungary and Japan. The process entails feeding PX 35 carbon fiber tow into a pultrusion die and, typically, infusing with a thermoset resin (vinyl ester, epoxy or polyurethane), to produce plate 3-6 mm thick, in widths of 75-300 mm. The unidirectional, laminate plate has a low void content (<1%), a density of approximately 1.55 g/cc, and can be specified with volumetric fiber content of 58-70%. A peel ply can be applied to both sides of the plate during the process and then removed prior to stacking within the spar cap tool. This provides a clean, activated surface for infusion and laminating the plates together to form the spar cap. Unlike fabric or prepreg prior to infusion, the properties of the plate have already been fixed during the pultrusion process, a feature that appeals to blade designers, certification agencies and manufacturers because it eliminates most of the potential for variation in the properties of the final part. »

Pultrusion can best prepreg in spars

Epsilon Composite (Gaillen en Medoc, France) has built a state-of-the-art pultrusion line for highly accurate fiber placement designed to maximize volumetric fiber content and compressive properties of the carbon/epoxy laminate. This roll of the company's 300-mm wide by 3-mm thick Carboglulam laminate, first shown at JEC World 2017, reportedly has a compressive strength significantly higher than laminate made from a widely used carbon fiber prepreg. Source | Epsilon Composite

Maxing out compressive properties

This last point is significant, because the mechanical properties of parts made from a unidirectional material are fiber-dominated — that is, when loaded in the tensile and compressive directions, as they are in a rotating turbine blade, the amount and type of fiber determines the performance (as opposed to multiaxial laminates, in which fiber orientations are varied, thus their impact on tensile and compressive strength also vary). For carbon fiber, the tensile properties are higher than the compressive, meaning, from a design perspective, compressive strength is the limiting property in a spar cap's construction. Any improvement in compressive strength, with respect to carbon fiber or glass fiber structures, that can be realized in neat material properties provides engineers with greater design flexibility. This fundamental principle also highlights the prime reason pultrusion has become the preferred method to manufacture carbon fiber spar caps.

In a unidirectional tape, laminate defects, such as voids or misaligned fibers, have an exaggerated, deleterious effect on mechanical properties, and can reduce even further the modest advantage in compressive strength carbon fiber wields over glass fiber. Employing pultrusion to manufacture spar cap laminates, says Romain Coullette, commercial director, Epsilon Composite (Gaillen en Medoc, France), makes sense because pultrusion is, arguably, "one of the most stable, repeatable *and* cost-competitive composites manufacturing processes."

In 2013, Epsilon launched its trademarked Carboglulam pultrusion process to produce stackable carbon fiber laminate for the manufacture of spar caps. Since then, the company has introduced a "next-generation" version of the composite, with improved compressive properties as benchmarked against a fabric and prepreg commonly used in structural turbine applications. It is targeted to spar caps for turbines expected to be operating in prolonged, high-velocity wind conditions.

The latest formulation features volumetric fiber content up to 70%, compared to the initial version, which had fiber content of ~60%.

Epsilon also designed a pultrusion system that controls and aligns each fiber independently to ensure accurate fiber orientation in the 0° axis, thus obviating potential micro-buckling. Lastly, the fibers are infused with a toughened epoxy system (as opposed to vinyl ester in the first formulation) with improved fiber/resin adhesion and higher interlaminar shear strength (>75 MPa). Coullette says an additional benefit of the laminate, which is also produced in rolls of various widths and thicknesses, with peel ply on both sides, is an improved modulus (168 GPa) facilitating the design of thinner spar caps, especially in the flange areas. That, in turn, permits a reduction in overall blade thickness.

Coullette says Epsilon is collaborating in several testing and development projects with customers, who currently use either glass or carbon prepreg to manufacture turbine spar caps, evaluating the pultruded carbon fiber laminate's performance and cost characteristics as a potential replacement material. Epsilon's pultrusion manufacturing facility, according to Coullette, has annual capacity of 1,500 MT.

Schell estimates that, globally, about 25% of wind turbines are now manufactured with carbon fiber spar caps. Although that figure is trending upward, it also underscores that most turbines are still built entirely from glass fiber composites. Is there a cut-off point, in terms of turbine size, at which engineering necessity would favor carbon spar caps over glass? "Large, glass-fiber spar » caps can be built simply by adding more material to achieve the required mechanical properties," he observes, "but at some point it becomes so heavy it makes more sense to use carbon."

Schell cites a 2012 study by Sandia National Laboratories (Albuquerque, NM, US) researchers comparing cost and performance of a 100m, all glass-reinforced "baseline" blade designed for a 13.2 MW turbine, to an identical, hypothetical blade substituting a spar cap made from unidirectional carbon fiber laminate. The analysis predicts a 28% mass savings (31,861 kg) for the carbon fiber spar vs. the all-glass variant. The weight savings derives from the fact that large-blade design is driven by fatigue life and panel buckling resistance. Reducing mass not only reduces the gravitational loads on the blades — thereby enhancing its fatigue performance — but it also facilitates the design of a spar cap 63% thinner than the baseline glass version, with reduced reinforcement required in webbing and along the blade's trailing edge. Further, there is the previously mentioned improvement in aerodynamic performance.

Schell says that when all cost/performance trade-offs are considered, as in the Sandia-type analysis, a solid case can be made for substituting carbon fiber for glass fiber in the manufacture of spar caps for turbine blades 55m long and longer.

Realizing that *in practice*, Schell allows, will hinge on sustaining improvements in both pultruded carbon fiber laminate cost and properties, especially compressive strength and modulus.

"Carbon will not buy its way on a blade because of hype…," says Nolet. "It must drive lower LCOE." But he expresses confidence that carbon fiber can and will do just that because it is part of a larger *system*. "Weight reduction in the rotor can drive reduced aero and inertial loading," he notes, adding that there are cascading benefits that often get overlooked. If blade weight is reduced, the size and, therefore, the weight and cost of the blade drivetrain also can be reduced. Each component — the input shaft, gearbox, pitch bearing — can be made less expensively, "ultimately reducing tower and foundation mass," he points out. "These savings can and likely *will* offset the cost of carbon over other material choices," he contends. "Therefore, they will positively impact the economics and ROI [return on investment]." CW

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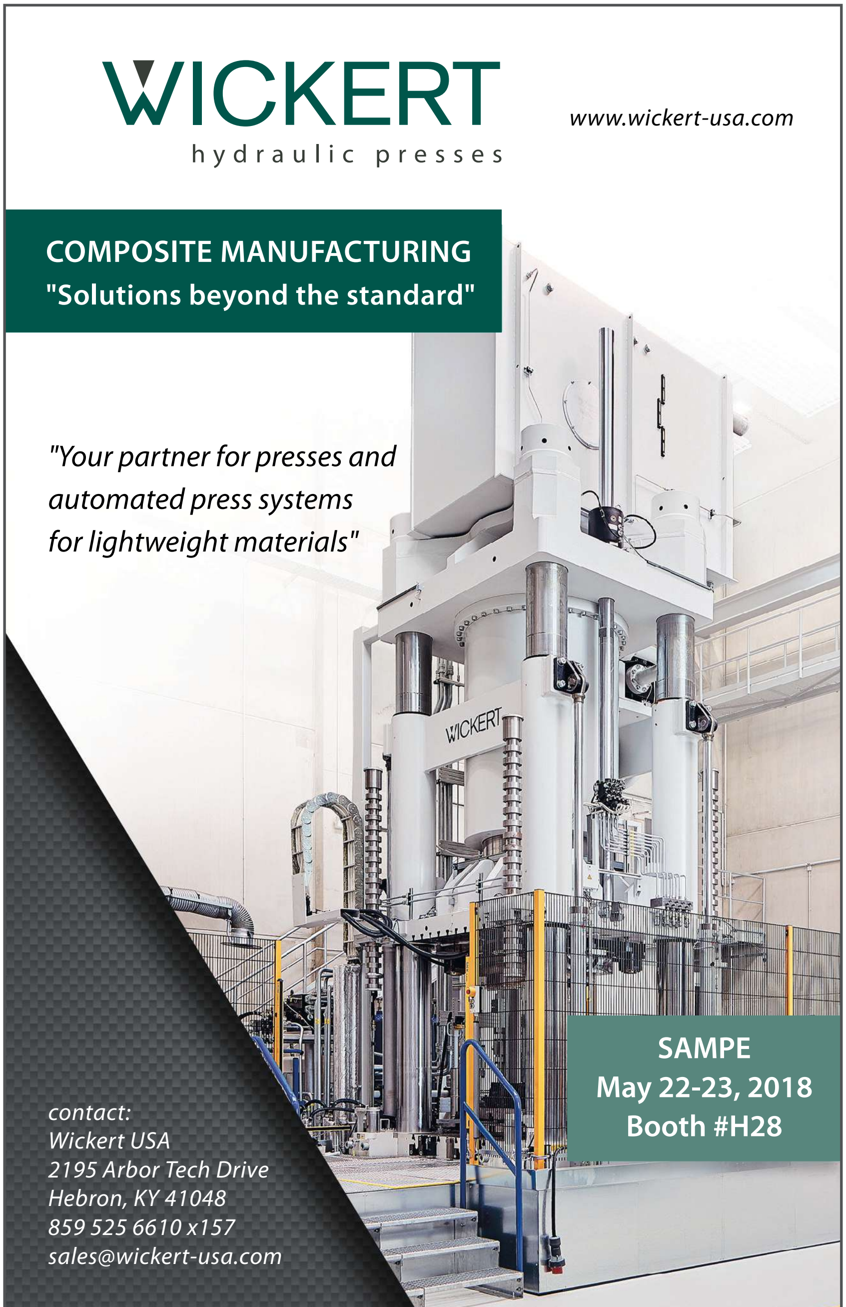

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The future of CFRP aerostructures assembly

Metrology, robotics and inline inspection cut cost, reduce shimming and enable future automated production of three vertical tail planes per day.

By Ginger Gardiner / Senior Editor

FLEXMONT vertical tail plane workcell

The FLEXMONT automated assembly cell cuts composite vertical tail plane (VTP) assembly time by more than 20%, reduces shimming and integrates continuous, vision-based quality assurance. It comprises two sub-areas, rib-shell assembly (left) and assembly of the VTP box (right), both using smaller, more flexible jigs and intelligent holding fixtures.

Source (all images) | Airbus / CTC / Fraunhofer IFAM

» In current widebody aircraft — the Boeing 787, Airbus A350 and the recently announced CR929 under development by the China-Russia Commercial Aircraft International Corporation (CRAIC) — composites comprise most of the airframe structures, including the fuselage, wings and vertical tail plane (VTP). This has not been the case so far in smaller-framed narrowbody aircraft, where weight is less of an issue and the increased complexity and expense of large composite assemblies are at odds with higher production rates and lower price tags.

One exception is the composite VTP pioneered by Airbus (Toulouse, France) in its A320 family of narrowbody aircraft. Looking forward to increased production rates, the company has recently sought to update the VTP's assembly process.

As part of the three-year FLEXMONT project (2013-2016), the Airbus VTP production facility in Stade, Germany, collaborated with German partners Fraunhofer IFAM (Bremen), the Composites Technology Center (CTC, Stade), FFT Aviation (Fulda-Rodges), Mahr Metering Systems GmbH (Göttingen) and QUISS AG (Puchheim) to develop a new, automated assembly process. The new approach cuts assembly time by more than 20%, reduces shimming and integrates a continuous, vision-based quality assurance system.

"This system, even if implemented on only one VTP assembly line — vs. multiple lines required today — can accommodate the high production rates being targeted for the future," says project manager and CTC engineer Alexander Engels. "We can also adapt this concept to other assemblies, like the wingbox horizontal tail plane and high-lift parts, like flaps."

Addressing current assembly issues

The original VTP design, completed in the 1980s, did not envision today's aircraft production rates. "It is, ergonomically, a nightmare," says Engels. "Areas for fastener installation are hard to reach. It relies on manual processes for application of adhesive and liquid shimming, and it requires special transport jigs and cranes to guarantee a rate of 40 aircraft per month." Airbus announced

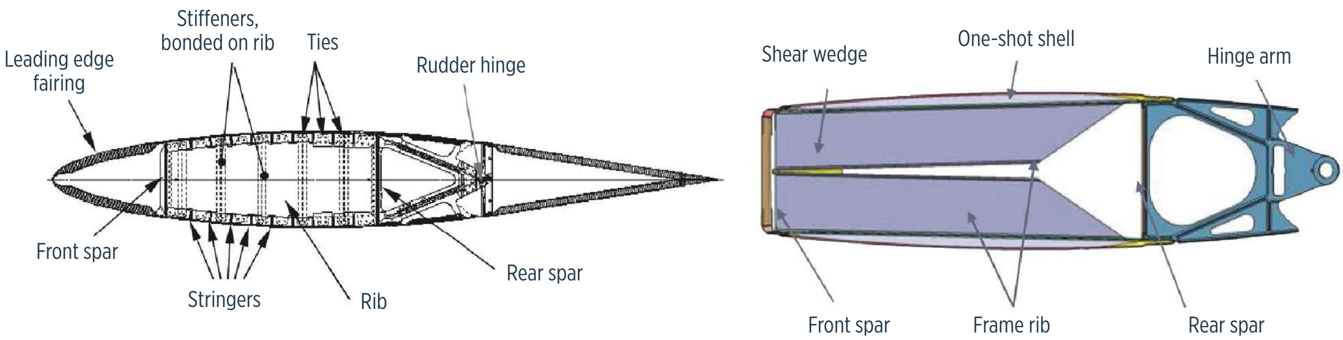


FIG. 1 VTP design: Old gives way to new

The FLEXMONT project was based on the VTP NG design (top view, right) vs. the original CFRP design for the A320 VTP from the 1980s (left).

in 2017 that its target is 60 single-aisle aircraft per month by 2019, which translates to three VTP assemblies *per day*.

With this in mind, the CTC developed a next-generation design, the VTP NG, which uses one-shot, foam-cored shells for the two large exterior surfaces, supported by bonded composite frame ribs (Fig. 1, above). The VTP's composite box is then closed out by joining prefabricated rear and front spars. FLEXMONT is a feasibility study based on the VTP NG design.

The VTP NG and FLEXMONT process developed symbiotically. The initial idea was to improve accessibility and reduce the number of parts and operations, aiming for more modular, ergonomic sub-assemblies and increased automation. Shimming would be automated and improved by developing a smart tolerance-management approach — an automated process that would adapt the quantity of material applied based on digital measurement of the gap between the surfaces to be bonded. "Based on the manufacturing process used for the VTP NG shells, we were not able to guarantee a gap below 0.3 mm, thus shimming was still required," Engels adds. The joint surfaces also would be plasma-treated for surface activation prior to bonding and both plasma treatment and adhesive application would be continuously monitored for quality assurance (QA). Parts handling would be entirely robotic and fixturing would also be "intelligent," aiming to avoid heavy, expensive jigs by pursuing adaptable, less part-specific designs.

Each partner contributed its expertise. CTC and Airbus handled development of the original concept, manufacturing and part design data, and assumed project management. Fraunhofer IFAM combined hardware, software and the collected data from all sources into a well-tuned, automated assembly cell. It also worked closely with QUISS, which delivered the vision system and algorithms necessary for integrating QA. Mahr Metering Systems supplied the shim adhesive metering equipment, and FFT Aviation built the fixture systems and FLEXMONT cell hardware.

Installation of ribs to shell

The FLEXMONT process comprises two major stations within the automated work cell: One handles assembly of the frame ribs »

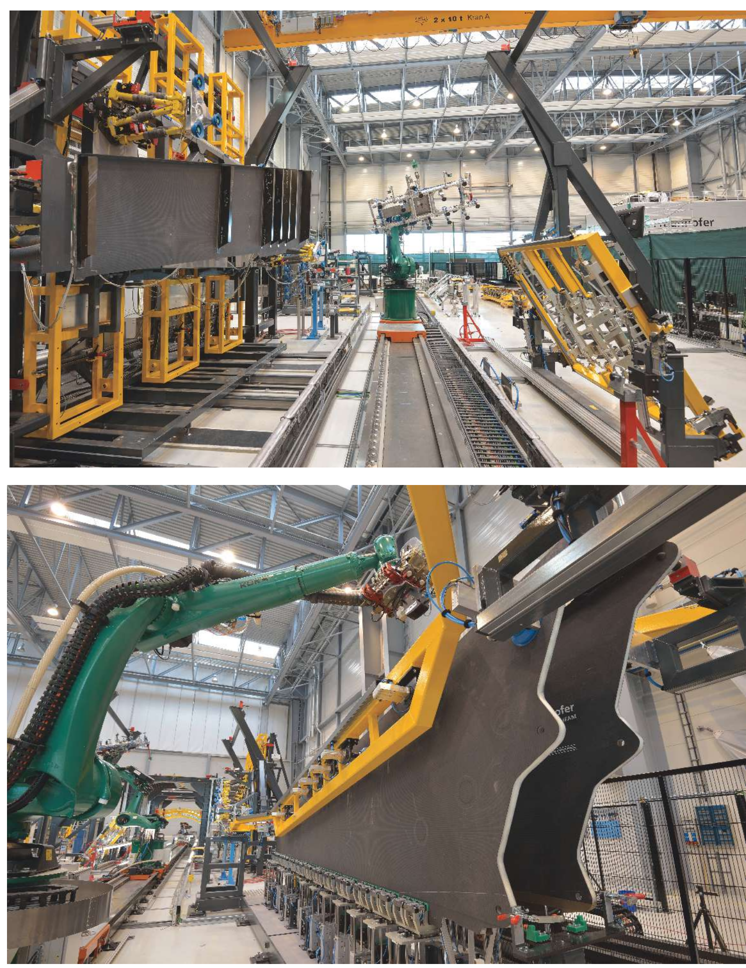


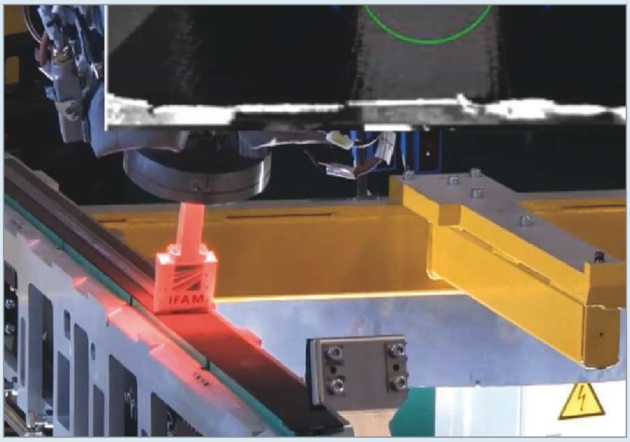
FIG. 2 Robotically reduced assembly time

In FLEXMONT's rib-shell assembly area (top photo), a robot with vacuum cup-equipped gripper (green unit in background) installs CFRP ribs from a universal frame (yellow unit at right) to the VTP shell section at left. Finished rib-shell sub-assemblies are then mated to the VTP rear spar in FLEXMONT's box assembly area (lower photo). The relatively inexpensive industrial robots used in both areas reduce assembly time and enable data-driven precision and inline inspection for improved quality control.

1 A composite VTP NG shell section is robotically placed into a flexible, automated holding fixture within the rib-shell assembly area.

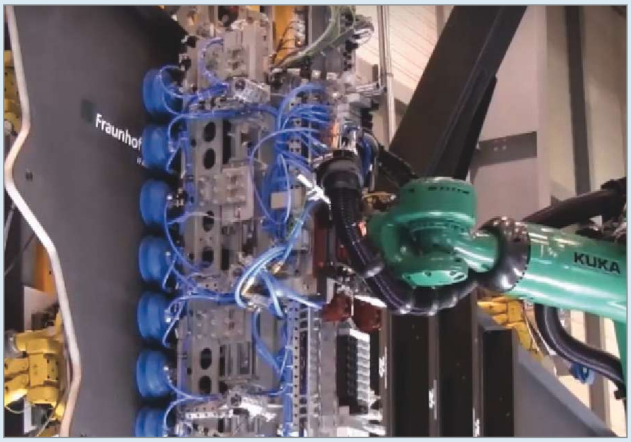
2 Before ribs are bonded to the shell, each is scanned with a laser measurement device as is the area of the shell where it is to be mated.

3 Rib and shell surfaces to be bonded are treated with atmospheric plasma to increase surface energy activation for higher-strength adhesive bonds.

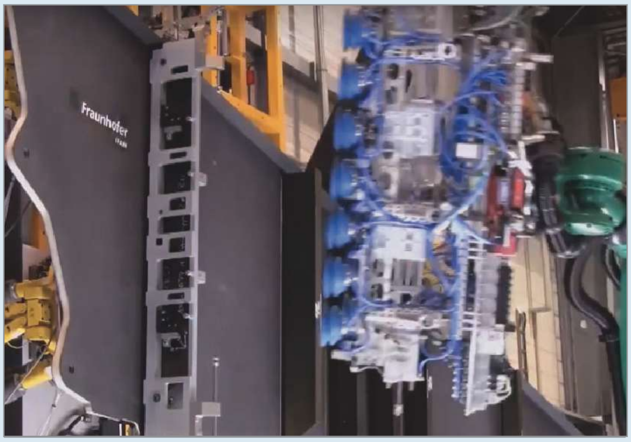


4 Automated application of shim adhesive using smart tolerance management system uses laser scanned 3D digital data to predict gap in bonded joint and apply material accordingly. Red light on application tool aids vision system data acquisition for inline QA.

5 Robot with flexible gripper system (blue vacuum cups) removes CFRP rib (mounted in aluminum fixture) from universal frame which can hold all 8 ribs needed for each VTP shell.



6 Robotic gripper places rib onto the shell.

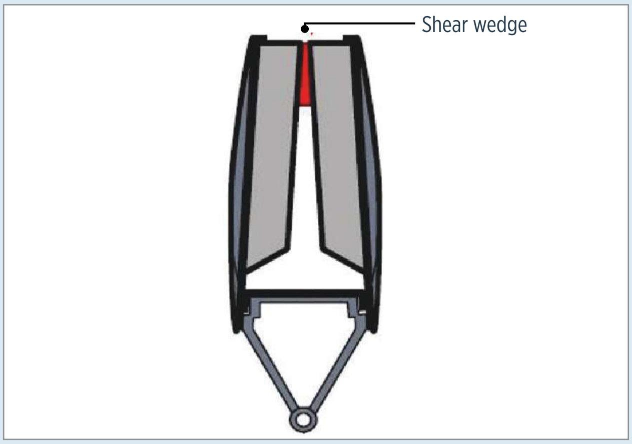


7 Robotic gripper withdraws, leaving the aluminum rib fixture, equipped with an inner tool to hold the rib onto the shell during adhesive cure.

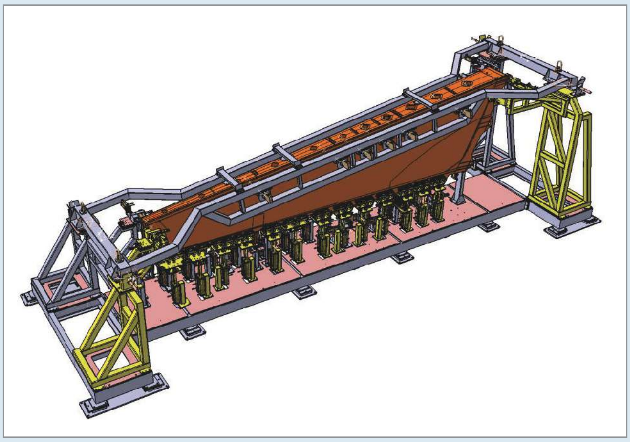
8 Laser scanning and plasma treatment of the rear spar right flange is followed by gap-adjusted application of shim adhesive in preparation for bonding with the right VTP rib-shell sub-assembly.

9 The right rib-shell subassembly is then transferred by the gripper-equipped robot and mated to the right flange.

10 Right-side clamping units in the box montage assembly fixture rise to apply the pressure necessary to both the shell and spar, ensuring a good bonded joint while the shim adhesive cures.



11 A shear wedge is inserted in between each pair of rib frames along the VTP, setting its aerodynamic exterior shape.



12 Dual robots are used to insert the wedges at the top of the VTP NG box within the assembly fixture.

FIG. 3 Sophisticated fixturing

The FLEXMONT box montage fixture includes two identical sets of actuated clamping mechanisms (green and gray elements in center of photo) which apply pressure on the rib-shell subassembly and mated rear spar flange to ensure a high-quality bonded and shimmed joint. This fixturing approach enables part-to-part assembly — vs. conventional fixed assembly — using adaptive joining based on data collected during the manufacturing process.

onto the cored shells, followed by box *montage*, or assembly of the VTP box (see opening image, p. 42, and/or view the video noted in Learn More, p. 48).

Operations within the rib-shell sub-area begin with robotic placement of a completed VTP NG shell section into a flexible, automated holding fixture (Step 1, p. 44). Standard industrial robots offer an economical solution, with increased flexibility and precision vs. the previous crane system.

Before ribs are bonded to the shell, each is scanned with a laser measurement device — the Leica (Unterentfelden, Switzerland) T-Scan TS50-CFK laser line scanner — as is the area of the shell where it is to be mated (Step 2). These scans are used to generate a 3D point cloud for each surface and are compared to the digitized design files in preparation for liquid shimming, a previously manual step. "This creates a virtual assembly where you can see if there will be any gaps in the rib-to-shell joint," Engels explains. This data set, which indicates potential gaps, is fed into the automated process to guide application of liquid shim adhesive.

Before the shim adhesive is applied, however, the surfaces to be bonded must be plasma-treated (Step 3). This increases the surface energy activation, resulting in better adhesion and increased bond strength. Again, the process is automated, using the same robot with a different end-effector. The plasma head is then swapped for a dosing head that mixes and dispenses the two-part, high-viscosity shim adhesive, and its application begins (Step 4). "The amount of shim/adhesive is varied by the robot speed," Engels explains. "This is determined from the digital analysis of the bonding surfaces and the virtual assembly. So, if the gap varies, the shim/adhesive application varies." The width remains the same, but the thickness changes. This is evident in the right side of the Step 4 image — more shim/adhesive can be seen at the rear of the rib and less at the front.

The red light that swathes the adhesive applicator is used to show contrast in the integrated vision system for QA. The vision sensor captures data, which are analyzed using an algorithm that checks tolerances and also detects anomalies, such as bubbles, in the shim adhesive material. "At the end of the application and scanning, the system will show a green window and 'IO' symbol if it is good," says Engels. "If this does not appear, then we have to interrupt the process, remove the liquid adhesive and reapply."

Adhesive is first applied to the rib, and then to the waiting shell section. The gripper used by the robot for the shell section in Step 1 had its origin in this part of the process. Each shell section in this VTP NG concept study receives eight ribs, each with a different length, thickness and orientation angle on the shell.

"We needed a grabbing system for every rib, but to develop one that would handle such a wide range, individually, would have been expensive and complicated," Engels explains. "Thus, we divided the grabbing system into two parts: a universal frame to hold inexpensive, simple aluminum rib fixtures, and then a more complex, intelligent robotic system for placement of each rib onto the shell. The simpler system accommodates the different rib geometries while the grabber system enables precise location." The robot with blue vacuum cup-equipped gripper approaches the large, yellow rectangular universal frame, clamps the rib/aluminum frame that is to be bonded and removes it (Step 5). The universal frame can hold all eight ribs, with the difference in length easily visible from the longest rib at left to the very short rib second from the right. The robot then traverses the workcell's linear rail and positions the rib on the shell. Required tolerances are maintained using a combination of CAD data on the rib and shell, plus topographical measurement data from the laser scan performed in Step 2.

"In order to bond the ribs to the shell, we must apply 0.4 to 0.6 bar of pressure, which equates to a force of several hundred kilograms for the largest ribs," Engels points out, "so we use the vacuum cups to press the rib onto the shell and apply this force. We can apply more than 1,000 kg with this system and simply switch off the vacuum cups that are not needed for the shorter-length ribs."

When rib and shell are joined, the robot retracts the gripper and moves to its next task. However, the aluminum rib fixture remains, equipped with an inner tool that holds the rib on the shell during adhesive cure (Step 6).

Although cure can be achieved as quickly as 1 hour, using applied heat, elevated temperature cure was not demonstrated during this project.

"The aluminum rib fixtures are cheap," notes Engels, "so it is easy to make many of these for bonding all of the ribs simultaneously." »

When the adhesively bonded joints are complete, the gripper is again used to remove the aluminum rib fixtures and return them to the universal frame.

Box assembly

Operations then move into the second area of the automated workcell, referred to as the *box* assembly station. Here, the shells and rear spar are assembled into the CFRP box, to which a front fairing and rudder at the rear will be attached for a finished VTP.

This second FLEXMONT work station is comprised mainly of an actuated assembly fixture with its own assembly robot. A prefabricated, C-shaped CFRP rear spar, >6m long, is loaded into the assembly fixture with its flat web facing up and flanges facing down. The sequence of laser scan, atmospheric plasma treatment and shim adhesive application steps completed for the rib-shell sub-assemblies is repeated in preparation for bonding the left and right shells to the left and right flanges of the rear spar. Accordingly, the right flange of the spar is scanned, as is the corresponding joint area on the right shell, and both are plasma-treated. "We again calculate the prospective gap in this joint and apply tolerance-adapted shim adhesive to the right flange of the spar, if required," says Engels (Step 7, p. 45).

The right rib-shell subassembly is then transferred by the gripper-equipped robot and mated to the right flange (Step 8). Dowel pins are inserted into reference holes in the right shell, which mate with holes in the spar flange. These mate the shell and spar until they can be clamped together by the joining fixture, the floor of which is equipped with 13 pairs of actuated clamping mechanisms along the right side for the right shell and a mirror set along the left side for the left shell. The right-side clamping units rise to apply the necessary pressure to the shell and spar, ensuring a good bonded joint while the adhesive cures (Step 9).

"Currently, temporary fasteners and manual clamps are used to hold conventional A320 VTP components during shim adhesive cure," notes Engels. "The FLEXMONT clamping system, however, is floating in the joining direction, providing adaptive joining with adaptive force to press the components together. This is part-to-part assembly, not fixed." This last point stresses FLEXMONT's departure from conventional aerostructure assembly,

LEARN MORE

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

Read more about CTC's new VTP design | short.compositesworld.com/CTCTour

A video of the FLEXMONT assembly process, titled "Automated vertical tail plane assembly" has been posted on YouTube by Fraunhofer IFAM | short.compositesworld.com/FLEXMONT

Read more about reconfigurable assembly tooling | short.gardnerweb.com/RecnfgTool where large, rigid assembly tools serve as a fixed holder for the first part, to which all other parts are attached. Instead, FLEXMONT attaches the parts to each other using a more process-flexible jig and metrology to maintain tolerances.

"We control the force and we have measured the parts in advance," Engels explains, "no additional quality inspection is required. Afterward, we use manual gauges to measure the gap between the shell and spar flange for validation of this process."

The same operations performed for the right shell and right spar flange are repeated for the left rib-shell subassembly and left spar flange. In the last step of box assembly, shear wedges are inserted in between each pair of rib frames (Step 10). This fixes the aerodynamic shape of the VTP exterior per the specified design tolerances. However, placing and pressing these wedges coated with a sealant/adhesive into the very narrow space at the top of the VTP NG box within the assembly fixture posed an accessibility challenge. In this research project, the solution was to attach a small, lightweight robot, as an end-effector, onto a larger industrial robot. Thus, the large robot positions the small robot, which inserts and presses the shear wedges into place.

Faster future development

The developments successfully demonstrated in FLEXMONT are impressive. "All of the operations shown in the Fraunhofer IFAM video result from pushing one button," emphasizes Engels. "The process takes minutes, not hours," he notes, but cautions that after the FLEXMONT assembly process is completed, joints must be reinforced with mechanical fasteners per current aircraft regulations (see Learn More). "Riveting and drilling processes are already state of the art and, thus, not considered in this project, but they would have to be implemented in a complete production system."

On the upside, it also uses one continuous tolerance system. "There is one continuous measurement system in this assembly process," Engels explains. "All of the measurement data can be combined because they all have the same reference system." This not only speeds the process but also drastically reduces complexity, errors and risk.

Engels explains that before this next iteration of FLEXMONT can be adopted for future production, validation will have to be completed not only for the major steps but also for every detail of the process and equipment. Use on future A320 aircraft *is* the long-term goal, but FLEXMONT's developments and demonstrated success to date give the nod to an optimistic outlook for composites in future narrowbody commercial aircraft assemblies. CW

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Additive manufacturing: Big and going commercial

A demonstration of large-format 3D printing delivers parts for an excavator cab, from CAD data to ready for assembly, in only five hours.

By Michael LeGault / Contributing Writer

»Large-format additive manufacturing (LFAM) is relatively new to the 3D printing marketplace but has quickly established a promising niche. Essentially, LFAM is a marriage of the motion systems used in today's precision CNC-machining or laser-cutting machinery and 3D printing/extrusion heads modified for use in the larger format. Although much attention has been focused on using large-format 3D printers to build tooling for composite molding processes, they have also found use in building finished parts themselves in one-off and very low-volume production. In either case, the technology is promising, and initial work, and the cost analyses derived from that work, suggests that large 3D printers, compared to current composite tooling and part fabrication practices, can offer significant cost savings, especially in total labor hours.

Benchmarking part-printing potential

Although development of the technology is ongoing, and the sample size of workpieces is still relatively small, an early demonstration

An additive manufacturing showpiece

A consortium of industry and academic partners collaborated in the design and build of the Additive Manufactured Excavator (AME), which was unveiled at the 2017 ConExpo/ConAGG show in Las Vegas, NV, US. Fully functional, the hydraulically powered excavator is the first with critical components built by means of additive manufacturing, including its cab, 3D printed from carbon fiber-reinforced ABS.

Source | Carlos Jones / Oak Ridge National Laboratory / US Department of Energy

3D printing and bridging gaps

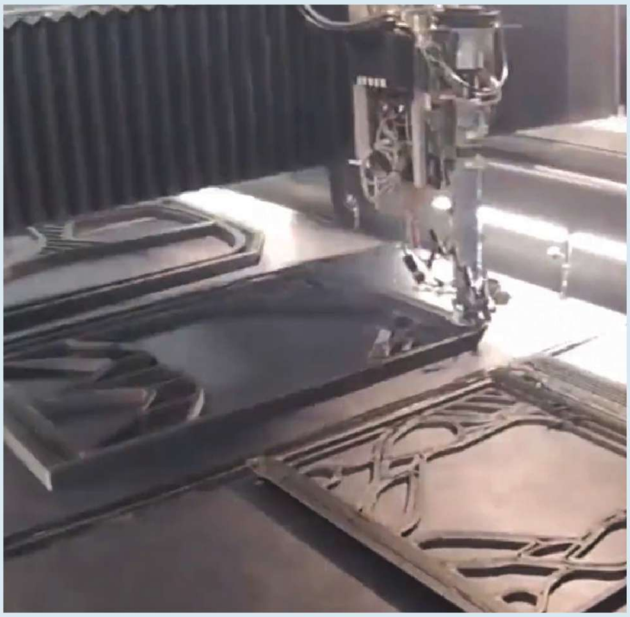
Small-format 3D printers can bridge a small gap during the printing process, because the very thin extruded bead cools and hardens in a fraction of a second. The volume of the bead extruded on the BAAM printer, however, typically needs a minute to cool. During that time, the weight of the bead could cause it to sag, so either the part or printing layers must be designed in a such a way that the printed beads aren't required to bridge gaps, or there is a means to support beads that must cross gaps of any significant length.

Source | Carlos Jones / Oak Ridge National Laboratory / US Department of Energy

project that entailed the printing of an excavator cab from carbon fiber-reinforced acrylonitrile butadiene styrene (ABS) provides a benchmark and insight into its capability to manufacture composite parts.

The cab was designed and manufactured by a consortium of industry and academic partners, called the Center for Compact and Efficient Fluid Power (Minneapolis, MN, US) using Cincinnati Inc.'s (Harrison, OH, US) trademarked Big Area Additive Manufacturing (BAAM) machine. The cab components were printed at the US Department of Energy's Oak Ridge National Laboratory (ORNL) Manufacturing Demonstration Facility (Knoxville, TN, US). Together with a 7-ft/2.13m long excavator arm, 3D-printed from carbon steel, and a 13-lb (5.9 kg) aluminum heat exchanger laser printed via a powder-bed-based process, the cab is one component of the first fully functional, hydraulically powered excavator with its key, critical components built using additive manufacturing technology. The project is referred to holistically as the Additive Manufactured Excavator (AME), and the machine was unveiled at the 2017 ConExpo/ConAGG show in Las Vegas, NV, US.

The cab was 3D printed with an ABS compound containing 20% chopped carbon fiber, supplied by Techmer PM (Clinton, TN, US) and now trademarked as Electrafil ABS 1501 3DP. The resin »



1 The six cab parts were printed as two sets of three. Pictured here, the BAAM extruder head begins to print the parts. The solid model of each part is exported as an STL file into software developed by ORNL that "slices" the part into discrete layers, which in turn are transformed into program code used by the machine to print the part. As printing proceeds, bead layers increase part thickness, and the parts become more clearly defined. Pictured here, from upper left to lower right, are the left side of the cab, the front or windshield area panel, and the back wall of the cab.

3 The external surface of the cab is sprayed with the self-leveling filler/coating, which is formulated to hide the print lines and to chemically bond to the carbon fiber-reinforced ABS substrate to provide a paintable surface.

All step photos courtesy of Carlos Jones / Oak Ridge National Laboratory / US Department of Energy

2 After printing, the parts are assembled with a combination of snap-fit joints, screws and adhesive. After assembly, the cab is masked, as shown here, to ensure that a patent-pending, self-leveling filler/coating is applied only to the external, paintable surfaces.

4 After the self-leveling filler dries, its surface and edges are sanded to provide a smooth, paintable surface. Then a primer (shown here) is applied to the coated, external surface of the cab.

5 The proprietary primer coating facilitates easy application of paint (shown here) to the carbon fiber/ABS cab.

6 In a final step, a clearcoat is applied to the paint, providing a Class A finish and gloss.

»

is specially formulated for pellet-fed, large-format printing, which, depending on the application, may require higher stiffness than achievable with similar glass-filled formulations. The resin system has a reported flexural modulus of 1.8 msi, compared to Techmer's 20% glass-filled grade, also targeted for BAAM applications, with a modulus of approximately 0.9 msi. The carbon fiber/ABS has a melt temperature in the 220-260°C range, a moisture content of 0.1% or less; and dries in approximately 4 hours at 80°C.

The 48-inch wide by 54-inch deep by 65-inch tall (1,219 mm by 1,372 mm by 1,651 mm) cab was printed in six separate parts (two sets of three) — four side panels (including a two-piece front panel comprising an upper and lower section) and a roof. The printer was Cincinnati's Size-2 BAAM system, which has a build envelope of 240 by 90.74 by 72 inches (6,096 by 2,305 by 1,820 mm) in the x, y and z dimensions, respectively.

Rick Neff, Cincinnati's additive manufacturing product and sales manager, says the critical components of the machine are the extruder and motion system, which facilitates fast, accurate part production. "We adapted a CNC motion system to a 3D printer, and program it with the same code we use for laser-cutting steel," he says, noting that Cincinnati developed the machine in cooperation with ORNL. The system uses a lightweight aluminum/honeycomb gantry and brushless magnetic linear servomotors with dynamic flow control that matches the extruder speed with motion of the head to deliver consistent bead width and placement. Nominal extruder speed is 2,500 ipm (63 m/min) in the x and y directions. The system's accuracy for absolute positioning and repeatability in the x and y axes is ±0.005 inch (±0.127 mm).

Real-world prototype

Although the cab was built as a prototype demonstrator, Neff emphasizes actual real-world structural parameters figured into its design, because the AME was to be operational. "We didn't just build a box with four windows," he says, reporting that engineering students from the University of Illinois who participated in the project used CAD software to design the parts, optimize the topology and meet anticipated structural loads. A key concern in terms of loading was crush-resistant occupant protection in the event of a rollover. As a prototype, the cab was neither tested nor qualified to a formal crush-resistance standard, but the intent of it was inherent in the design. When the cab design was finished, the CAD model of its parts was evaluated for the best way to print it. Each individual solid-model part is exported as an STL file into "slicer" software developed internally at ORNL, which effectively slices the parts into discrete layers; these layers, programmed into machine code, form the base units, as it were, of the build using BAAM.

Each part was printed horizontally, on the BAMM machine bed, with wall thickness built up by laying successive beads of material over the semi-dry, solidified layers beneath it. The carbon fiber/ABS was extruded under approximately 13 MPa of pressure with a nominal bead width of about 0.25 inch/6.35 mm. Because the material requires about one minute to cool and solidify before another layer of material can be deposited over it, to avoid sag, distortion or other dislocation, the machine is programmed to avoid any machine lagtime by keeping the extruder busy elsewhere depositing beads, and then returning it to deposit another bead when a safe margin of safety for cooling has been allowed. The cab components have an average wall thickness of 1.5 inches/38.1 mm, or about 10 bead layers (see Steps 1 and 2, p. 52).

The same, but a big difference

Small-scale 3D printing machines, using methods such as stereolithography (SLS) and fused deposition modeling (FDM) technology, have been on the market for more than 20 years, whereas large-format machines, BAAM is one of two current commercial options, have only been available recently. The two technologies invite comparison; the cab build highlights the similarities and differences.

For one, today's LFAM systems use extruders modeled on or take their inspiration from the FDM systems used in the small-format 3D printer segment. The extrusion process and fundamentals of building up parts by layers are, except for scale, identical. "You can learn a lot about 3D printing from a desktop machine before you make a part on the BAAM," Neff says. At the same time, he cautions, there are *functional* differences. A small-scale 3D printer, which typically is used to make models and prototype parts, extrudes a fine, thin bead of plastic, which cools and solidifies nearly instantly. There is, then, no necessity for the one-minute cooling interval noted above. This allows bridging between parts and part sections with no support structure. On the other hand, a large-format 3D printer, such as BAAM, is designed for commercial applications, so making large parts via extremely thin layers would be cost *in*effective. Consequently, large 3D printers extrude a bead perhaps 25 or more times thicker. The thicker bead, however, won't bridge much more than a very small gap without sagging, a fact that has implications for part design (see the photo and caption on p. 51).

A thicker, wider bead also precludes the printing of a part with smooth visible surfaces, necessitating finishing — machining, filling, sanding, priming and painting or other finish coating.

With that caveat, there is an exceptional upside in the potential to exploit a modelmaking/CNC machining-free way to make production tooling and a tooling-free way to make one-off and few-of-a-kind finished parts. "Additive manufacturing allows you to redesign things in a way you never have before," says Lonnie Love, a corporate research fellow at ORNL. Love, who oversaw the printing of the cab at Oak Ridge, says the slicing software is the » critical component, which generates the toolpath and automates the process that enables CNC machining to become, essentially, CNC "adding."

After printing, the parts were removed from the machine bed and the cab was assembled with a combination of snap-fit joints, screws and adhesive. The team used a rubber-hardened PLIOGRIP epoxy adhesive from Ashland (Columbus, OH, US), specially formulated for bonding plastic parts.

When the cab was assembled, Tru-Design LLC (Knoxville, TN, US), a composite manufacturer and R&D company, and a member of the Oak Ridge Carbon Fiber Composites Consortium, carried out a detailed surface finishing process, entailing the following steps: masking, spraying of self-leveling filler/coating, sanding, applying of primer, painting and clearcoat (see photos).

PPG (Pittsburgh, PA, US) supplied the primer, paint and clearcoat. John Miller, VP of sales with Tru-Design, reports that the self-leveling filler/coating, a patent-pending material, called Tru-Design TD Coat RT, achieves a Class A surface finish on carbon fiber-reinforced composite parts. Tru-Design, which had previously participated on a project to 3D print a *Shelby Cobra* body with BAAM (see Learn More, p. 57), also conducted at ORNL, developed the material jointly with the Polynt-Reichhold Group (Durham, NC, US). The latter manufactures the product, which is sold exclusively by Tru-Design for printed and molded composite tooling and parts, as well as a high-temperature version for tooling used in autoclaves.

> Tooling appears to be the best near-term application for LFAM, but one-off parts are viable options.

Love calls the material a potential game-changer for achieving Class A finishes with carbon fiber composites. "When the parts come off the printer they have a sort of corduroy, ribbed texture," Love says. "In the *Shelby* project, we learned sanding on carbon fiber-reinforced plastic is a nightmare."

The TD Coat RT, which cures in 4 hours at room temperature, serves a three-fold purpose: it fills the corduroy-like print lines and other surface imperfections, acts as a sealant and chemically bonds to the composite substrate. The coating provides, after a light hand-sanding, a smooth, paintable surface. Using the material, Love reports, the excavator cab surfaces were finished in a fraction of the time required for comparable surfaces on the *Cobra*.

For precision parts and most tooling, application of the coating must be accounted for in the thickness of the final printed part, Love says. In the case of the excavator cab, the effect of the coating on final thickness was insignificant. Of greater potential consequence, especially for the design of mating surfaces, is part shrinkage: The carbon fiber/ABS resin used to print the cab shrinks about 0.5%, a shrinkage rate similar to injection molded parts.

Going commercial in aerospace

Neff reports selling three BAAM systems to three customers, which now use them to make production tooling for aerospace composite parts. Indeed, tooling currently appears to be best near-term commercial application for LFAM. But Love believes there are certain applications in which using a large-format printer to directly manufacture one-off parts makes sense. He reports using ORNL's BAAM machine to make furniture, including a bar counter, benches and stools, for a company pavilion at the 2016 Design Miami Show. In a unique twist to this project, the parts were made from a bio-composite, comprising bamboo fiber and PLA resin compounded by Techmer PM. The project consumed more than 10,000 lb of resin.

Large format 3D printing is admittedly in its early stages, with designers and fabricators still progressing through a learning curve while machine suppliers strive to enhance and hone features. On the wish list for Neff is off-the-shelf machine programming software, as well as a full suite of design optimization and simulation software for the additive process. Currently, he reports, design optimization relies too much on trial and error.

Already viable, LFAM's wider adoption and commercial success hinges on how well it outperforms current toolmaking and fabricating practices. That, in turn, depends to a great degree on how soon and how extensively the wish lists of printer suppliers and users are granted and fulfilled. CW

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Read this article online | short.compositesworld.com/AM-BigandC

Read *CW*'s coverage of another BAAM demo online in "ORNL 'prints' Shelby Cobra for Detroit Auto Show" | short.compositesworld.com/3DCobra

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Service & repair: Optimizing wind power's grid impact

As wind farms surge into the electrical mainstream, a fast-growing industry works to maximize the service lives of the composite blades that harvest the power of the wind.

By Donna Dawson / Senior Writer Emeritus

As a sustainable clean energy source, wind power has taken off. Today, it's less an alternative energy source and more mainstream. (See the Side Story titled, "Wind energy: A worldwide phenomenon," p. 61.) For that reason, its reliability has become increasingly crucial.

Virtually every rotor blade on a wind turbine in the megawatt range — generally 25-30m in length and some much longer — is a composite today, according to Derek Berry, senior wind technology engineer for the National Renewable Energy Lab (NREL, Denver, CO, US). Most blades are made from glass fiber, but a growing number of longer blades are now of hybrid glass/carbon fiber construction, using standard thermoset and thermoplastic resins, with metal lightning protection systems and metal bolts attaching the blade's root to the turbine's rotor.

Like their aerodynamic cousins, aircraft wings, wind blades must be inspected and, when damaged, repaired. Because their operation is, like aircraft, so critical to the life of the communities they now serve, their performance, and the performance of those who inspect, service and repair them, must meet certain standards. Here, *CW* examines the sophisticated industry that has grown up around inspection and repair of turbine blades.

Wear and tear

Airplane wings and wind turbine blades alike suffer erosion, lightning strikes, impact damage and ordinary operational fatigue, all of which affects

Blade inspection & repair

It's a growing and critical facet of the fast-emerging field of wind turbine operations and maintenance (O&M). Inspection *and* repairs of aging blades are commonly made while blades are still attached to the rotor hub. The means to accomplish both vary widely.

Source | Rope Partner

FIG. 1 Rope-access/hands on inspection

Rope access inspection methods permit close visual and photographic inspection. Rope-access practitioner REETEC (Bremen, Germany) uses as internal camera that can inspect nearly 100% of a blade interior at a rate of up to six blades per day.

Source | REETEC

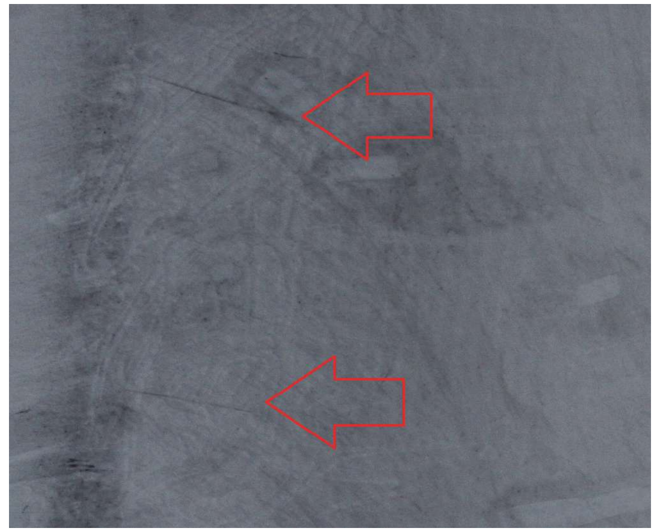

FIG. 2a Ground-based inspection

Less-labor-intensive, ground-based telephotography and zoomable telescope inspection methods developed by Performance Composites (Abilene, TX, US) spotted these hairline cracks in this wind blade surface.

Source | Performance Composites

their aerodynamic performance. Diminished aerodynamics of the blades can also impair their production of power.

The leading causes of damage to wind blades in operation are lightning strikes and leading-edge erosion, the latter caused primarily by particles in the air bombarding the front edge of the airfoil (blade tip speeds can reach *200 mph*).

In the category of operational fatigue, wind blades are in a class by themselves: "Wind turbine blades are some of the most highly cycled structures in operation — well over an *order of magnitude more* than even aircraft wings we see in one design lifetime of flights," says Berry. The extreme cycling can result in unseen, difficult-to-detect types of damage that might not immediately affect performance and production, Berry cautions. "Over years of cycles, blades can develop stress fractures, fatigue cracking near the root section where higher bending loads occur, resulting in cracks in the composite laminate or in the blade skins or shear web inside the blade, or in the bond line — in the adhesive joint that holds the two shells of the blade together. Those kinds of damage might not immediately result in a noticeable decrease in aerodynamic performance, an increase in drag or a decrease in power output. However, left unrepaired, they could lead to catastrophic failure, either a blade failure with the crack propagating or — worst case scenario, which we fortunately don't see much of anymore — a blade flying off the turbine!"

Preventive maintenance is key

Regular inspection can reveal damage *before* it becomes catastrophic failure. "In the past 5-10 years, end-users have been learning how much downtime [when the turbine is stopped] can affect their profit from energy production," Berry says, "and what they can do to minimize downtime" caused by the need for »

FIG. 2b Ground-based optical inspection

These severe shell fractures at a trailing edge also were found by telephotography and zoomable telescope inspection.

Source | Performance Composites

FIG. 3 Targeted inspections

A rope technician from Vestas – American Wind Technology (Portland, OR, US) inspects a blade on a turbine in Fowler, IN, US, after installing vortex generators.

Source: Vestas

unanticipated repairs. He says the most effective way to minimize downtime is good inspection — an *annual* inspection of all blades *at the minimum* — and repair where needed.

Wind blades are different from wings in one other respect: wings can be inspected and repaired under controlled conditions when the airplane lands. But wind blades, mounted on massive towers, reaching 80m and more in height, don't land. They must be inspected and, if necessary, repaired, under less than ideal conditions. Surprisingly, nearly all blade inspections actually can be done *uptower*, that is, with the blade on the rotor but stopped.

Who inspects and how?

Inspections are performed by a wide range of maintenance providers, including major blade manufacturers Vestas (Vestas – American Wind Technology, Portland, OR, US), LM Wind Power (Kolding, Denmark) and Siemens Gamesa Renewable Energy (Hamburg, Germany), as well as dedicated suppliers, such as BS Rotor Technic USA (Anaheim, CA, US), Performance Composites (Abilene, TX, US), Rope Partner (Santa Cruz, CA, US), InspecTools (LaSelva Beach, CA, US), MISTRAS Rope Access Services (Reno, NV, US), REETEC GmbH (Bremen, Germany), Sky-Futures (Hayes, Middlesex, UK), SkySpecs (Ann Arbor, MI, US) and others — for onshore and offshore wind turbines. Additionally, DNV GL-Energy (Arnhem, The Netherlands) offers a complete range of inspection services and regulations for onshore and offshore wind turbines and their components. »

SIDE STORY

Wind energy: A worldwide phenomenon

Wind energy association WindEurope (Brussels, Belgium) reports that the wind industry contributes €36 billion to the European Union (EU) gross domestic product (GDP) and supports 263,000 jobs in Europe. At the end of June 2017, the European Union had a total of 159.5 GW of wind power capacity installed (48% in Germany). And the *U.S. Wind Industry Fourth Quarter 2017 Market Report* released by The American Wind Energy Assn. (AWEA, Washington, DC, US) reported 89 GW of wind power installed across 41 states, "enough to power 26 million American homes" — attracting US$14 billion annually in private investment to US wind farms over the past decade and employing US 102,500 workers at the end of 2016. By that year's end, wind had become the largest new source of electrical energy, outpacing coal, natural gas and hydro-electric sources.

According to Navigant Research (Chicago, IL, US), wind farm developers in the Asia-Pacific region led wind turbine order capacity with 2.8 GW of turbine orders signed in the first half of 2017. Navigant's report, *Wind Turbine Order Tracker 4Q17*, says global wind turbine orders announced in the first half of 2017 reached 11.6 GW, representing a decline from 14.7 GW in the second half of 2016 and 13.4 GW in the first half of 2016. "Despite this year's decrease in order capacity, the average turbine rating continues to grow, with many of the top turbine vendors having weight average ratings near 3 MW or higher," says Adam Wilson, research analyst with Navigant Research.

Wind energy's growth is now truly global in scope: Siemens Gamesa (Zamudio, Spain) alone reports that it has installed 700 MW in Turkey, has signed on to do 1 GW more there *and* has won a contract to provide wind company F.L. Wind with 18 G97 2-MW turbines for its 36-MW Jelovaca project in Bosnia and Herzegovina. The order marks its second turbine supply deal within the country. Bosnian utility ERS also sought consultants in 2017 to help with the environmental and social scoping aspects of developing a 48-MW wind farm in the country, according to the company. The project is expected to feature 16 3-MW turbines. Saudi Arabia's Renewable Energy Project Development Office is planning to host at least two renewable energy leasing rounds this year, seeking developers for 800 MW worth of wind farms. Brazil, meanwhile, already has 13 GW of installed wind power capacity in 518 wind farms, according to its National Wind Energy Assn. Given current contracts, Brazil will reach nearly 19 GW of installed capacity by 2023, the organization says. And Thai solar firm Superblock has unveiled plans to add several wind farms with a combined capacity of 700 MW in Vietnam.

Notably, the Pyeongchang 2018 Olympic Winter Games were entirely powered by wind energy. The total generation capacity reached 203 MW, exceeding the Games' required capacity of 194 MW by 104%.

In all, the wind energy industry added 52.6 GW of installed generating capacity in 2017, bringing the world's total near 540 GW, says the Global Wind Energy Council (GWEC, Brussels, Belgium). "The numbers show a maturing industry, in transition to a market-based system, competing successfully with heavily subsidized incumbent technologies," adds GWEC secretary-general Steve Sawyer.

Today, four main uptower blade inspection methods are available:

Hands-on, rope-access inspection. All access to blades is gained via lifts in the tower, if available, or climbing tower ladders, with crew members tethered to a safety cable. Rope technicians leave the tower through the nacelle at the top, bringing their gear and tools with them. They rig their rope systems to themselves in the nacelle and are ready to access the blades.

Rope Partner's director of business development Josh Crayton, says that, in terms of blade inspection, rope access is "absolutely the best quality! You can touch the blade, you can feel it." Another advantage of the rope-access method is that inspectors have access to both the inside and outside of the blade. Founded in 2000 and said to be the original rope-access provider in North America, Rope Partner at one time or another has worked with every kind of end-user, Crayton explains — private owners and wind farms, wind blade manufacturers and wind system OEMs. "Six years ago, we were the first to create long-term blade maintenance programs with our clients and we have been executing them ever since. These programs have proven to reduce the number of catastrophic blade failures for our customers," Crayton states.

"We can typically inspect one full rotor, all three blades, inside and out, including lightning protection verifications, in one day, with a crew of two or three," Crayton says. More time may be required for blades that exceed 50m in length. Inspection in the confined space *inside* a blade may require a crew of three to meet federal safety requirements.

FIG. 4 Repairs require worker support

Regardless of the inspection method or methods used, most repairs that follow must be performed by technicians uptower and with plenty of support. That can take the form of scaffolding (see opening photo) or be as simple as the suspended basket pictured here, both used by Rope Partner (Santa Cruz, CA, US).

Source: Rope Partner, Photo: J. Castagnetto

REETEC technicians perform rope-access *internal inspections* of blades up to 100m long using its computer-controlled, motorized high-definition (HD) camera, which provides photo comparisons, videos and records. "This enables an exact tracking of discovered damages and subsequently an analysis of the damage evolution over time," explains REETEC sales director Claus Sejersen. The video is conveyed directly to the technician operating the equipment, who makes close-up photos of any suspicious areas. The photos are analyzed by experts in the office, in cooperation with the blade inspector. "There is no real-time transmission of video takes to the customer, but severe damages will be communicated to the customer directly after the finding," Sejersen says.

Ground-based telephotography and digiscopic imaging. Performance Composites' preferred blade inspection tool is telephotography, using its high-powered, zoomable 480-mm telescope (24-60x zoom) with high-quality, brilliant crystal optics. Craig Guthrie, partner and director of technical operations, describes the process: "All four sides of all three blades are scanned in detail and any anomalies found are documented immediately," he notes. "If a different blade pitch is necessary, we radio the technician controlling the rotor movements. Once an issue is identified, our trained blade technician, positioned 50-60m from the tower base, can quickly swap the eyepiece on the scope for a mounted/inline 18MP Digital single-lens reflex (DSLR) camera." The digital camera, capable of *digiscopy*, or »

FIG. 5 **As good as being there**

This photo of blade damage was taken by a camera mounted on a drone from InspecTools (LaSelva Beach, CA, US), during its use to enable remote inspection of turbine blades at Sheringham Shoal Offshore Wind Farm in the North Sea, operated by Statoil.

Source | InspecTools

the capture of detailed images from a great distance, is used to capture images of the issues found but never to perform the visual inspection. This is because the multitude of mirrors, filters and focal point optics that are built into the camera come between the eye and the surface of the blade. Ground-based photographic methods, in general, can provide thorough and cost-effective inspection of blade *external* surfaces.

Ultrasonic, thermographic or other NDT from crane-based platform/basket. Rocky Duffey, Vestas' blades project manager, says that in some cases Vestas uses uptower ultrasonic, thermographic or other NDT — perhaps from a platform or basket — as well as tap testing, depending on the focus of the inspection. But such efforts are typically a follow-up to a visual inspection format. "Imagery is usually our first inspection step, by drone or ground photography," he notes. "If we are looking for a very specific investigative or failure mode, then we would employ more sophisticated methods. We select the method that will give us the information that is most cost-effective and still provides the information we need."

Many of the blades manufactured by Vestas have a structural spar and when damage is indicated over the spar, "we need to go uptower for an invasive inspection to determine if the spar itself has been damaged," Duffey says. "Typically, we do that sort of inspection either by suspended basket or hydraulic lift. It depends on the goal, what sort of assets are available, and what we are looking to accomplish."

Uptower inspections via drone. The advent of unmanned aerial vehicles (UAVs) has resulted in technology now useful in blade inspection. Because the ultimate goal of blade inspection is to deliver findings quickly so effective action can be planned and pursued in a timely manner, there is potential for fast deployment and real-time reporting in camera-bearing aerial drones. The technology is still developing, but it holds much promise to expedite diagnosis and repair.

Currently, drones are operated by technicians on the ground. They capture and process images for subsequent review by inspectors. Remote operation of drones from a wind farm site office is a technology advancement that could ultimately speed the process. And custom drone software and image recognition software packages are increasingly making drone inspections and analysis of defects faster and more cost-competitive. Today, software can be programmed for defect recognition and cropping of images to help the reviewer hone in on specific areas of damage, says Chris Bley, VP business development for drone inspection service InspecTools. And future implementation of *Computer Vision* systems could enable automatic sight, analysis and understanding of the obtained image or sequence of images. "Getting the highest priorities of damage to the right people as quickly as possible promotes timely and cost effective maintenance and repair decisions and actions," says Chris Bley. He describes InspecTools' end-to-end inspection strategy as very powerful and capable of collecting high-resolution imagery of all surfaces of a blade in about 5 minutes. The drone »

FIG. 6 Close up and focused

A drone operated by SkySpecs (Ann Arbor, MI, US) executes an intimate inspection of a wind turbine. Source | SkySpecs

can stay up for as long as 35 minutes. "We fly a very powerful drone because it's windy, obviously, on wind sites. We do a total of four passes: two on each side of the blade. We get very high resolution imagery that we upload via our software program."

The blades are parked in position for drone inspection: If just one blade is under inspection, the blade will be positioned straight down, but if all three blades on a rotor are to be inspected, the blades are parked with one at 0° ("like a candlestick") and the other two at 45° angles (visualize 12/4/8 on the clock).

The individual images are processed and uploaded into InspecTools' custom software, *WindAMS*, which "organizes each image to the specific location on the blade and then the blade on the wind turbine and then the turbine on the wind site and then geographically by sight," explains Bley. "On a macro-scale, we use Geographic Information Systems (GIS) organization methodology to keep track of the location of the affected turbine (and, thus, its blades), and the attention that each needs." InspecTools evaluates the images and selects those that appear to show damage. Bley cites its use of *algorithms* for data analysis as the type of improvement that is saving time and money. Algorithm analysis sharpens the focus on affected areas, he explains.

The company manufactures its own drone for offshore inspection, with a 42-megapixel, full-frame Sony Alpha 7RII professional camera, and uses a drone platform from DJI (Shenzhen, China) that includes a 20-megapixel X5S camera. "We've also started using infrared cameras for wind blade inspections, which is helping us to better see problems in the laminate providing a different heat signature," Bley says.

Sky-Futures (Hayes, Middlesex, UK) conducts visual and thermal inspections of blades by its drones, onshore and offshore, worldwide, operated by a remote pilot and qualified inspection engineer who operates the camera and conducts the inspection. Its license from the UK Civil Aviation Authority (CAA, London) limits maximum height of operation to 400 ft/122m. "For larger turbines, the company operates under an individual safety case for that specific task," says Chris Blackford, COO for Sky-Futures. "Blade size has never been an issue. The focus is total safety and high quality, ensurable and repeatable data sets." Damage is reported through Sky-Futures' cloud-based portal *Expanse*. Blackford says *Expanse* manages data securely in the cloud, allowing users to quickly and intuitively build inspection reports that present the inspection findings against a 3D model of the wind turbine.

Another drone resource is SkySpecs (Ann Arbor, MI, US). "We do not have any wind turbine size limits," says Theresa Trevor, SkySpecs' director of marketing. "Our system does not need to know which make and model of the turbine, the length of the blades, or the position of the blades during inspection. All of this is determined by the drone when it takes off." An inspection of one turbine takes about 15 minutes to complete.

The drone is automated and operates itself, but is monitored by a qualified operator on the ground, as required by federal aviation regulations, Trevor explains. After takeoff, however, the drone reportedly completes the entire inspection without any operator input. Damage is reported through a customer Web portal, where all the reports are accessed. All damage that is seen is identified, classified, measured and ranked by severity. The damage data is stored and tracked, so any changes can be seen in subsequent inspections. SkySpecs makes recommendations for repair on severe damage. "Future products will provide higher levels of analysis and will streamline O&M processes," Trevor says.

Full service: Inspection + repair

The inspection method selected by a wind power operator can depend greatly on the price quoted for an inspection — which, in turn, depends on location, on turbine downtime considerations — and on the *scale* or number of turbines at the location. In general, rope access inspections average one turbine per day (depending on the number of damage hot spots found); ground-based inspections, about five turbines per day; and drone-based, 10 or more per day.

The inspection *type* is another criterion for decision. Inspections by hands-on rope access are mostly visual, but are followed »

FIG. 7 Offering inspection flexibility and convenience

This drone inspection offshore of Denmark (drone provided by Sky-Futures, Hayes, Middlesex, UK) illustrates how inspections, can be conducted on site, with drones controlled from from a boat (or truck or on foot). Inspections are not concluded, however, in real time. Videos and/or photos must be downloaded and digitally processed before review later by inspectors. Source | Sky-Futures

by measurements and tap testing, where indicated, to determine the extent of the damage. Ultrasonic or other NDT testing also is possible but "rarely done on blades uptower in an operating, online state unless for a major known serial issue," says Rope Partner's Crayton. Any damage identified, however, is measured, documented and photographed.

Most of the companies that perform inspection also offer repair services. And the blademakers who offer inspection also maintain maintenance and repair crews. Vestas – American Wind Technology, for example, is not only a global wind turbine builder, but also offers full spectrum maintenance service for Vestas-manufactured wind turbine blades *and* those built by other manufacturers.

Most don't limit themselves to a single form of inspection, either. Although Performance Composites, for example, considers telephotography inspection from the ground its first option, it also offers drone inspection and uptower inspection via rope or crane-based platform access for onshore installations. Guthrie points out that although both ground telephoto and drone inspection methods are capable of capturing high-quality images of the blade surface, only the former is capable of enabling real-time image review. Although this delay could be eliminated in the near future, the drone's video recording or overlapping images currently cannot be viewed onsite, but must be reviewed later by inspectors after images are downloaded and digitally processed.

Those without the ability to perform all forms of inspection can contract with those who do. InspecTools, for example, contracts with Vestas and with Rope Partner, among others, to perform drone inspections for them and subsequently deliver software findings.

Moreover, for the past several years, Guthrie says, Performance Composites has primarily focused on uptower blade *repair* and has trained its end-user *customers* in inspection procedures. "Many of them did not have a budget in place for blade inspection," he explains. "So, no one was properly inspecting the blades for years on end. We decided to give up the majority of our inspection work and provide our equipment and low-cost training so that proper blade inspections could occur without waiting for funding of an outside source. This has worked well for us and for our customers."

Although most repairs can be done uptower, Vestas' Duffey explains, "If a blade is damaged too severely, we need to drop it down for repair." But, he adds, "That can usually be done on site even in the middle of winter. If this occurs in a very cold climate » such as Colorado, for example, we'll cover the portion of the blade we're working on, sealing it off from the environment, and set up an indirect fire heater and dehumidifiers, if necessary. We do what is needed to get the environmental conditions within our operating spectrum in order to do a reliable repair." In a very rare case, a blade might come back to the factory for repair.

Perhaps the most critical issue, from the customers' point of view, is not the methods of inspection or the technologies employed, nor when and how the blades are repaired. Ultimately, the blades are repaired by people. The concern is, are those who repair them composites-capable? Berry and others, therefore, stress the importance of blade repair technicians having the correct skills. "The end-users I've talked to have complained that they don't always know what they are going to get when they hire a repair crew. They feel they can't always expect a standard level of expertise for repair in the field." (See Learn More.)

Because of the nearly infinite variety of composite materials forms and properties, standardization has been a composites industry struggle. But Berry says NREL participated in drafting a new wind blade design and manufacturing standard through the IEC International Standards Group (Geneva, Switzerland), which also addresses operation and maintenance. DNV GL-Energy recently published a blade standard (DNVGL-ST-0376) for Renewables Certification that includes in-service inspections and maintenance and repair of in-service damages, among other guidelines, with basic guidelines for blade repair.

For its part, the American Composites Manufacturers Assn. (ACMA, Arlington, VA, US) offers its certificate in wind blade repair (CCT-WBR) and the American Wind Energy Assn. (AWEA, Washington, DC, US) offers publications on recommended practices for operation and maintenance of modern wind turbines that include wind turbine blade condition monitoring.

Berry notes that NREL is moving toward workforce development, including training for wind blade repair, acting in conjunction with the Institute for Advanced Composites Manufacturing Innovation (IACMI, Knoxville, TN, US), ACMA and select local community colleges. The idea is to use NREL's Wind Technology Center in Boulder, CO, US, and its Composites Manufacturing Education and Training Facility (CoMET), which was commissioned in 2017 in a collaborative effort between NREL, IACMI, the Department of Energy and the State of Colorado.

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Read more online about turbine blade repair in the following:"Wind blade repair: Planning, safety, flexibility" | short.compositesworld.com/BladePlan

"Wind blade repair: Safety and quality" | short.compositesworld.com/BladeSafe

"Gurit blade repair system receives GL certification" | short.compositesworld.com/GuritBlade

Vestas and other blademakers also offer training in composites repair, as does Abaris Training (Reno, NV, US).

Blade maintenance is big business

Certainly, the need is great. Make Consulting (Aarhus, Denmark) predicted in 2014 that the turbine inspection and repair market will flourish: In 2014, Make said global wind turbine installations had surpassed 300 GW and that an increasing number of turbines were coming off warranty. It's *Global Wind Turbine O&M* report expected an additional 300 GW of capacity additions over the following six years, creating "significant opportunities for the wind turbine operations and maintenance (O&M) sector." The addressable market inspection/repair was expected to exceed US$13 billion in "revenue opportunity" by 2020, driven by an installed base that could reach nearly 700 GW, globally. "The O&M market will experience double-digit annual growth until 2020, providing a robust market for a wide variety of stakeholders." For those capable of reliable blade inspection, there is plenty to do. CW

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Wide-use windsurfing board

Making the windsurfing sport available to all

Source | COBRA International

Former windsurfing race champion Bruce Wylie, now the head of COBRA International's (Chonburi, Thailand) watersports business unit, saw his sport losing numbers. That concern was echoed by retailers, who were seeing a downward trend in windsurfing board sales, in part because of the growing dominance of heavy boards with massive sails, designed for high winds and extreme conditions. Wylie wanted to develop a new windsurfing board that could function equally well for the racing enthusiast, those who teach students new to the windsurfing sport and even for those who would simply use it like a stand-up paddleboard on windless days. In short? A board so simple it could be enjoyed by a first-timer, yet offer the option of fleet racing to the more advanced sailor.

A year ago, the COBRA team started work on prototypes, inspired by classic race boards, but also referencing the latest design ideas. Wylie knew that his solution would need to balance weight with long-term durability and low cost. To make the board, a lightweight expanded polystyrene (EPS) core, with the desired shape and relaxed "rockers" (the small upturns at the board's front and back that enable easy flat-water gliding), is carefully encapsulated with varying weights of commodity chopped strand fiberglass and open structure "combi mats." (The latter are a combination of discontinuous fiberglass strands stitched to a woven fiberglass fabric.) The result is wet out with a foaming, bio-based epoxy resin system from **Sicomin Epoxy Systems** (Châteauneuf les Martigues, France). The foaming action during infusion creates a foam "sandwich" skin structure that stiffens the laminate.

Dubbed the Windsurfer LT, the new board — 3.7m long, 65 cm wide, and weighing 15 kg — is similar in size to the first windsurfing racing boards of the 1970s, but is 6.5 kg lighter. Windsurfing organizations worldwide are reportedly happy with the design and several have adopted the board as standard equipment for Windsurfer Class racing. CW

Composites Events

May 16-18, 2018 — Shanghai, China
SAMPE China 2018
sampechina.org

May 21-24, 2018 — Long Beach, CA, US
SAMPE 2018 Long Beach
nasampe.org/events/

June 13-14, 2018 — Novi, MI, US
CW amerimold 2018
amerimoldexpo.com

June 13-14, 2018 — Novi, MI, US
CW Composites Overmolding: A 1-minute cycle time initiative
compositesovermolding.com

June 20-21, 2018 — Nottingham, UK
Composites Innovation
compositesinnovation.com

June 21-23, 2018 — New York City, NY, US
Composites Pavilion – American Institute of Architects Convention 2018
conferenceonarchitecture.com

June 27-28, 2018 — Chicago, IL, US
The Future of Composites in Transportation
jeccomposites.com/knowledge/international-composites-agenda/future-composites-transportation-jec

June 27-28, 2018 — Las Vegas, NV, US
Global Composites 2018
globalcompositesconference.com

July 10-12, 2018 — Nottingham, UK
ICMAC 2018 – 11th Int'l Conference on Manufacturing of Advanced Composites
icmac2018.org

July 15-21, 2018 — Paris, France
ICCE-26, 26th Annual Int'l Conference on Composites/Nano Engineering
ice-nano.org

Sept. 5-7, 2018 — Novi, MI, US
SPE Automotive Composites Conference and Exhibition (ACCE)
speautomotive.com/acce-conference

Sept. 5-7, 2018 — Shanghai, China
China Composites Expo 2018
chinacompositesexpo.com

Sept. 10-12, 2018 — Toulouse, France
SpeedNews 19th Annual Aviation Industry Suppliers Conference in Toulouse
speednews.com/aviation-industry-suppliers-conference-in-toulouse

Sept. 10-15, 2018 — Chicago, IL, US
IMTS 2018
imts.com

Sept. 11-12, 2018 — Chicago, IL, US
AM2018: Additive Manufacturing Conference at IMTS
additiveconference.com

Sept. 11-13, 2018 — Southampton, UK
SAMPE Conference 18 Southampton
sampe-europe.org/conferences/sampe-conference-18-southampton

Sept. 18, 2018 — Augsburg, Germany
Experience Composites
experience-composites.com

Oct. 2-4, 2018 — Tampa, FL, US
IBEX 2018
ibexshow.com/show-info

Oct. 3-4, 2018 — Loughborough University, UK
Composites in Sport
compositesinsport.com

Oct. 15-18, 2018 — Dallas, TX, US
CW CAMX 2018
thecamx.org

Oct. 30-31, 2018 — Bremen, Germany
ITHEC 2018 – 4th Int'l Conference and Exhibition on Thermoplastic Composites
ithec.de/home

Nov. 5-6, 2018 — Stuttgart, Germany
4th Int'l Composites Congress (ICC)
composites-germany.org/index.php/en/dates/4th-icc

Nov. 6-8, 2018 — Stuttgart, Germany
Composites Europe
composites-europe.com

Dec. 4-6, 2018 — La Jolla, CA, US
CW Carbon Fiber 2018
E-mail sstephenson@compositesworld.com

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SHOWCASE

Wood/carbon composites for architecture

Innovative organic architecture enabled with wood/carbon laminates, software tools.

By Sara Black / Senior Editor

» Of the market sectors featured in *CW*, the one in which the design flexibility of composites is most on display is architecture. A case in point is a new building concept developed by Digital Architects (Vienna, Austria), which combines wood with carbon fiber composite to form organic shapes for load-bearing structures. Company principals are Atanas Zhelev and Mariya Korolova, former students of acclaimed British-Iraqi architect Zaha Hadid, the first woman to win architecture's top Pritzker Prize and known for fluid, sweeping and organic forms. Considerable effort went into a recent design by Digital Architects and its partners to create a submission for a library design competition in Varna, Bulgaria, a 46m, tree-like wood/carbon composite structural façade, undertaken in cooperation with Archicoplex (Tokyo, Japan) and that firm's architect Daisuke Hirose. Zhelev and Korolova led its development in collaboration with Universität Innsbruck (Innsbruck, Austria), epoxy resin partner Bodo Möller Chemie (Offenbach am Main, Germany) and simulation software partner Altair Engineering Inc. (Troy, MI, US).

"I think composite structures open up new possibilities for the designer to achieve more expressive surfaces, continuous shells, with very elegant and light profiles. There is always this passion in architecture to overcome gravity and lighten your building," says Zhelev. Although it ultimately was not selected, the striking design demonstrates composite technology's considerable potential for architectural innovation.

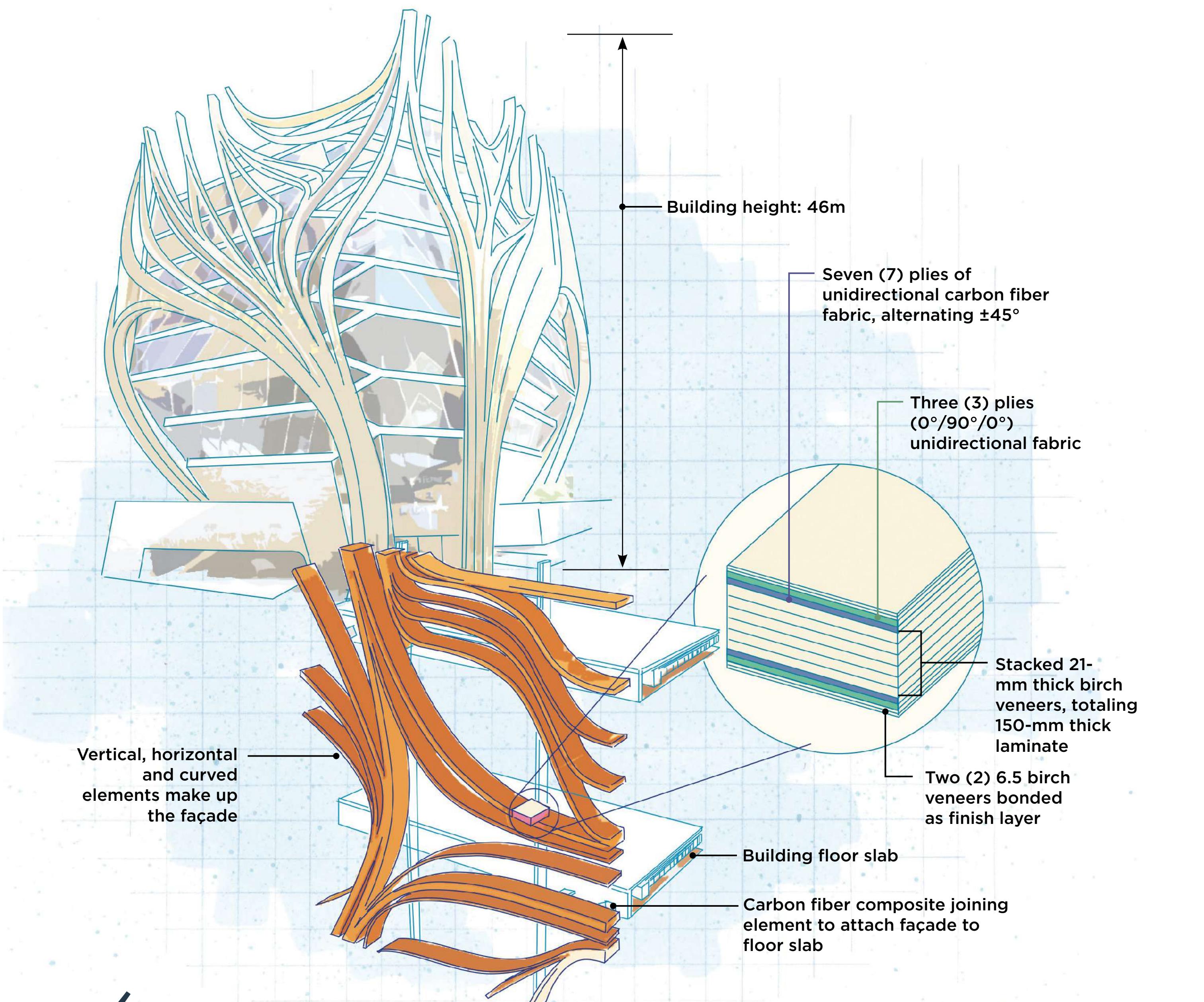
Making a supportive structure

Because the library is adjacent to Varna's monumental Soviet-era city building, the architects proposed a modern organic shape, equally expressive, to provide a counterbalance and a new city landmark. And, says Zhelev, the goal was to move beyond the conventional to define a flowing structure that would also support the building from the *outside*. Considerable design and testing was required, says Markku Palanterä, director of global composites business development at Altair and former CEO of Componeering Inc. (Helsinki, Finland), which developed the ESAComp software used by Digital Architects during the process (Componeering was purchased by Altair in 2017).

"We wanted a façade system which would be not only a shading element and an expression of identity, but an integral structural element of the building, capable of carrying between 10% and 30% of the building load," says Zhelev. Those structural loads for the 12-story building were

Freeing creativity in construction

An international design competition for the Varna, Bulgaria, regional library generated hundreds of entries, among them this organic concept from the team at Digital Architects (Vienna, Austria) and partner Archicoplex (Tokyo, Japan) and that firm's architect Daisuke Hirose. The tree-like façade would have been made from a wood/carbon fiber composite laminate. Source | Digital Architects



DESIGN RESULTS **Varna City Library Wood/Carbon Composite Façade**

- Thin, glue-laminated plies of wood veneer, alternately stacked, with woodgrain at 0°/90°, form a strong laminate core that can be shaped into a lightweight façade capable of carrying up to 30% of the building's structural load.
- Multiple unidirectional carbon fabric sandwich the wood laminate core, with plies at 0°/90° and ±45°, to impart structural strength for load-bearing applications and prevent delamination.
- The façade enables design and contruction of a building interior without support columns, acts as a louver system to control incoming light, and is connected to floor slabs by means of an innovative joint design.

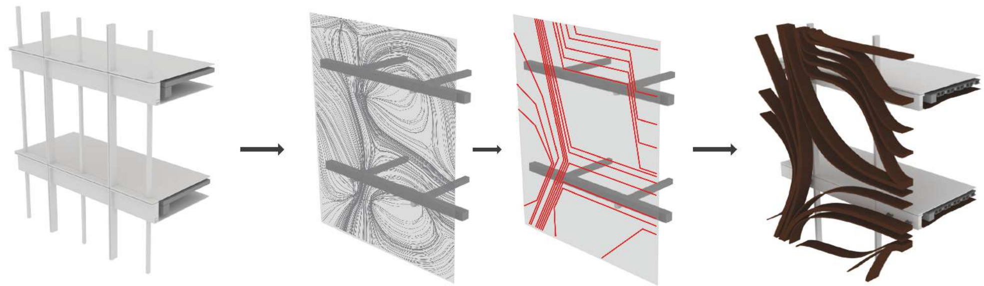
Illustration / **Karl Reque**

calculated and then, he says, "rationalized" or extracted from the irregular structural force "flow" acting on an imaginary exterior supportive wall, to form a structural system — not made up of rigid columns, but organic vertical, horizontal and curved elements that looked like trees (see opening image, p. 76). To realize these, the architectural team employed ESAComp for preliminary design of a wood/carbon laminate, to analyze structural component behavior and develop a structural joint to attach the façade to the building's floor slabs.

The laminate would be made up of stacked high-quality, straight, fine-grain wood veneers, kiln-dried for moisture control. These would be glue-laminated into preformed shapes, based on the position they occupy in the façade. Multiple unidirectional carbon fabrics would then be adhered to this wood laminate core, »

Digitally determined flow

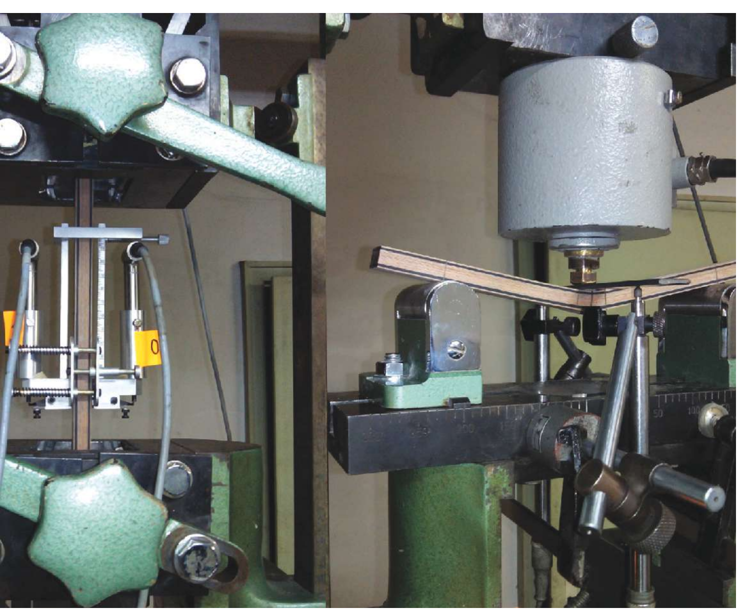
This graphic shows how the forces acting on the 12-story building's façade were "rationalized" or extracted from the irregular structural force "flow" acting on an imaginary exterior supportive wall. The flow led to the creation of vertical, horizontal and curved tree-like elements. The architectural team employed ESAComp for preliminary design and analysis of structural component behavior. Source | Digital Architects



forming a sandwich structure to impart structural strength for bearling loads and preventing delamination (see drawing, p. 77).

First, says Palanterä, it was necessary to understand the laminate behavior of both the wood and the combined materials: "What is the difference between varying thicknesses of wood in a laminate, and the location of the carbon layers? How could we achieve a material with well-distributed elastic behavior in all directions?"

Zhelev says ESAComp was a key to understanding the wood laminate *before* adding in the carbon plies. The software has an extensive material library with thousands of composite materials, and it includes a compilation of wood species. Veneer choices were narrowed to larch, ash, beech and birch. "Given the short timeframe for the Varna submission," says Palanterä, "the architects could quickly select materials, apply the loads and generate the design without having to first generate a finite element analysis [FEA] model."



Testing for true performance

Small test coupons of the wood/carbon laminate were destructively tested in accordance with the modified version of the European Standard EN408 for glued-laminated architectural timber structures. Source | Digital Architects

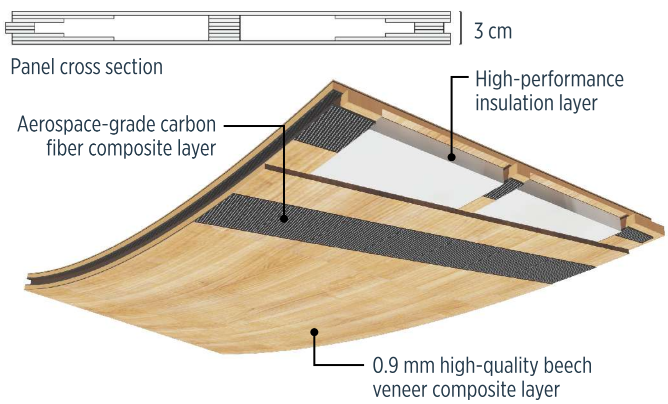
Although all the species had similar performance, measured by 4-point bending, tension strength (parallel to the grain) and shear strength, birch was ultimately selected not only for its strength but also because of its wider availability. Then, combinations of thickness and grain orientation were virtually tested to determine the ideal laminate. The strongest and most balanced was of alternating grain orientation, with seven, 21-mm veneers cross-laminated to form a 150-mm laminate core thickness. A key element was the wood-to-glue ratio, points out Zhelev: "The key was a well-balanced composite, without relying too much on either the adhesive or the wood."

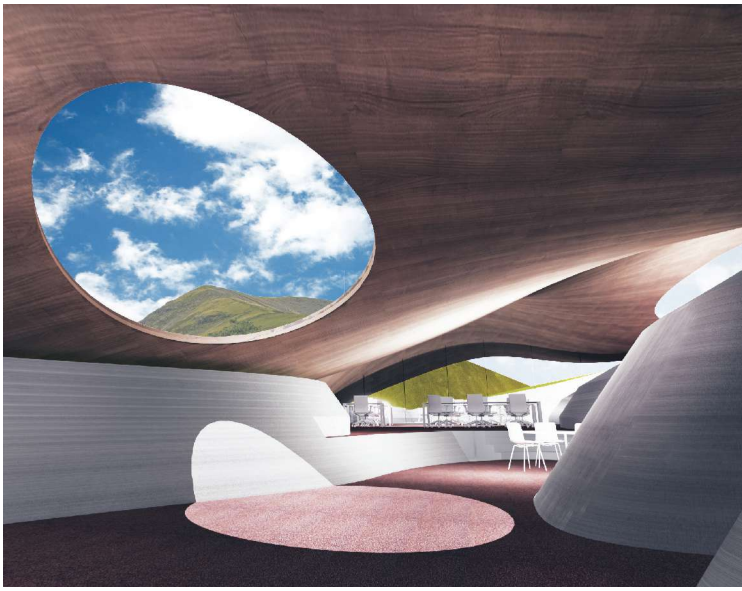
Engineering a superior laminate

The group next looked at the location and orientation of carbon fiber plies, and, says Zhelev, "We wanted to see the difference between how unidirectional fibers and a twill weave would behave, to get the desired stiffness, cost and ease of manufacture."

Based on Altair's HyperWorks structural analysis, the architects found that bonding seven plies of unidirectional carbon fiber, in an alternating ±45° orientation, bonded on each side of the wood laminate core, followed by three layers of cross-plied (0°/90°/0°) unidirectional carbon fiber, significantly increased the overall modulus and safety factors compared to using only ±45°, or only cross-ply. Says Zhelev, "The reason for this is because the wood fibers are also oriented more or less 0°/90°, so we are sandwiching the 45° carbon between the 0°/90° wood and 0°/90° carbon. This makes the structure harder to delaminate." And, the unidirectional carbon fiber performed better than the twill. Two birch veneer layers would then be bonded over the carbon fiber, top and bottom, as a decorative finish.

To verify the ESAComp modeling results, the team obtained wood and uni carbon samples, prepared test coupons, and destructively tested them to a modified version of the European Standard EN408 for glued-laminated architectural timber structures (see photo, at left). Uni fabric made with Toray Industries Inc. (Tokyo, Japan) T700 carbon fiber was supplied by Easy Composites (Staffordshire, UK). Says Zhelev, "We were pleased to discover that the coupons tested 10-15% stronger than the digital model predicted, with a controlled failure response. The composite was actually two times stronger in tensile strength, on average, than steel, likely because of the high quality of the wood we were able to obtain."





New vistas for wood/composite

The Adaptive Grid Monocoque (AGM) System is a roof construction concept of curved wood/carbon composite panels developed by the architects Zhelev and Korolova. It can be used to create thinner panels than metal-centric roofs for long-span installations, with reduced material use and cost.

Rendering source | UAV Learning Center / designed by Atanas Zhelev and Mariya Korolova within Studio Kazuyo Sejima, Institute of Architecture, University of Applied Arts Vienna

Using the optimized wood/carbon composite laminate from the preliminary design, Zhelev and the architectural team began scaling up to the full-sized façade. The structure was divided into three simplified main façade elements: vertically oriented, horizontally oriented and transitional elements having different radii of curvature. Each was examined for structural and wind load cases. The ESAComp analyses showed that the vertical elements could easily handle the building and wind loads, with a safety factor of 10, but the horizontal elements needed to be twice as thick as the vertical elements, to handle compression loads, as well as out-of-plane shear imposed by potential earthquake loads. Likewise, curvatures greater than 60° also required a double thickness to preserve adequate safety factors. Here, explains Zhelev, "we employed a design trick where several separate vertical elements would come together to curve into a thicker horizontal beam."

LEARN MORE

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

Listen to Atanas Zhelev describe the Varna library façade project in a recent *CW* Webinar | short.compositesworld.com/CWWeb-VBL

For the adhesive, The Digital Architects team needed one that could withstand high heat without losing structural strength. Working closely with development partner Alexander Teufl at Bodo Möller-Chemie, it selected a high-strength, two-part, low-temperature-cure Araldite structural epoxy (Huntsman Advanced Materials, The Woodlands, TX, US). Rubner Holzbau (Ober-Grafendorf, Austria), a specialist in large timber structures, was considered to fabricate the full-scale elements. Had the façade been built, the adhesive would have been applied in an automated process and the elements shaped with heat and pressure in large jigs.

The final design challenge was joining the wood/carbon trees to the building's structure and floor slabs. The architectural team didn't want to drill holes in the laminate or introduce metallic supports. The solution was a series of aluminum honeycomb-cored carbon composite joining members, which would have been bonded to the façade, then inserted into slots in the building's concrete floor slabs and bonded with an epoxy concrete compatible with the wood and concrete. Joint analysis performed in ESAComp determined the joining member thickness and validated the solution.

Moving forward with AGM for composite roofs

An outgrowth of the Varna Library concept is the Adaptive Grid Monocoque (AGM) System, a roof construction concept of curved wood/carbon composite panels (see artist's concepts, above). Zhelev says his group has improved the laminate's material strategy to create thinner panels, one-tenth the thickness of current curved roof spans, to reduce material usage and cost yet support high-performance, continuous long-span installations. An integrated heating concept will enable oven-free cure of the structural adhesive within the AGM panels. The AGM concept will be on display at the American Institute of Architects (AIA) 2018 convention in New York City, June 21-23. Concludes Zhelev, "We believe that with more and more composites coming to architecture, over the next 5-10 years the price of large-span composite structures will get lower compared to steel structures of the same size, especially if such structures have challenging and unusual shapes." CW

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