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6.9 kg with CFRP: WORLD'S LIGHTEST FOLDING BIKE

APRIL 2018

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COLUMNS

FEATURES

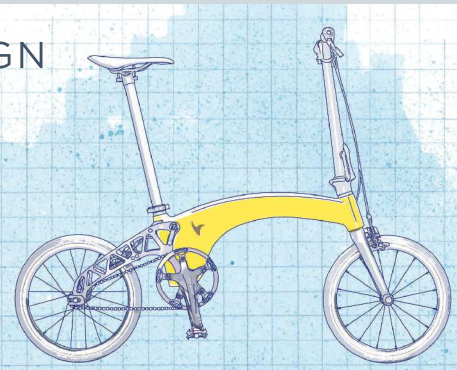
» DEPARTMENTS

» ON THE COVER

Architectural modelmaker and biking enthusiast Petre Craciun designed, and motorsport and advanced-engineering group Prodrive (Banbury, Oxfordshire, UK) refined and now builds, the *Hummingbird*, this 6.9 kg bike (that's right, the whole bike, not just the frame), which can fold down in little more than a minute to suitcase-size for easy portability on bus or train. Get the story behind the design on p. 44.

Source / Prodrive

FOCUS ON DESIGN



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» As I write this, we here at *CW* are just back from JEC World 2018 in Paris, France (March 6-8), and I'm reminded, again, that no matter how long you've worked in the composites industry, spending even a few hours at JEC World is akin to drinking water from a firehose. The show encapsulates in one (large) physical space all of the dynamism and creativity that composite materials and manufacturing processes have to offer. To absorb and comprehend even a fraction of it all would seem a Herculean feat.

What an acquisition tells us about our industry's future.

Still, if you are there all three days and visit with as many people as we do, it's always possible to discern recurring ideas, themes and trends that offer a few signals, at least, about where composites are, and where they are headed.

Indeed, we heard repeatedly at the show that the two major commercial aircraft OEMs, The Boeing Co. (Chicago, IL, US) and Airbus (Toulouse, France), are both in the throes of conducting serious trade studies of potential materials for use on next-generation commercial aircraft.

The particular aircraft in question are the Boeing NMA (New Mid-market Airplane, a replacement for Boeing's 757), the Boeing 737 and the Airbus A320. The NMA is necessary because Boeing now has a product gap between its largest 737 variant and the composites-intensive 787. The 757 had filled that gap, but Boeing stopped making that plane in 2004. The official launch of the NMA has been "imminent" for several months, reportedly because Boeing is still finalizing details of the plane's configuration. A sticking point appears to be the size and manufacturer of the plane's engines. Boeing reportedly is targeting 2025-2026 for its entry into service.

The 737 and the A320, the workhorses of the commercial aerospace industry, are highly profitable for their respective OEMs, and represent the world's largest-volume commercial aircraft. Although both planes were updated a few years ago, with new engines and other features, they are due for clean-sheet redesigns, possibly starting in the early 2020s.

So, as Boeing and Airbus watch the aerospace world evolve, the question facing the engineers who must design the NMA and redesign the 737 and A320 is, *Where and how do we apply composites?* And while that is not a settled matter, one thing is becoming increasingly clear: When composites are next applied on major aerostructures, there's a good chance they'll have a thermoplastic matrix (see Part 2 of *CW's* ongoing discussion of promising research toward that end on p. 34). This fact has the aerospace composites supply chain diligently assessing its ability to meet the needs of those who will build next-generation aircraft.

It was to that end that on March 14, less than a week after the show, the world's largest carbon fiber manufacturer, and supplier of almost all carbon fiber for the Boeing 787, Toray Industries (Tokyo, Japan), announced that it will pay more than US$1 billion (€931 million) to acquire TenCate Advanced Composites (Nijverdal, The Netherlands), a specialist in thermoplastic as well as thermoset prepreg. There had been talk before JEC that TenCate was seeking a strategic partnership, and at the show TenCate officials confirmed that the company was on the market.

In the composites industry, US$1 billion acquisitions are rare and, thus, important. Second, and more specifically, Toray is well known for its careful and thoughtful decision making. Many will recall that it committed to vast increases in its carbon fiber output only *after* Boeing and others committed to carbon fiber for commercial airframes. Indeed, the suddenness of the TenCate acquisition and the investment's size alone are enough to make the entire industry sit up and notice. Now, Toray has, effectively, placed a US$1 billion bet on its future. Given this, is it not reasonable to conclude that Toray must firmly believe thermoplastic composite structures will be a major part of one or more next-generation aircraft program? If so, it must firmly believe that TenCate is necessary to help it meet that demand.

Time will tell if this bet is a good one, but early signs suggest it is.

JEFF SLOAN — Editor-In-Chief


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Data infrastructure in composites manufacturing: A growing need

» In recent conversations at industry events, I have encountered a growing number of composites engineers who look bewildered when I mention mylar and fiberglass templates. Although this trend is a disconcerting sign of my lengthy career, more significantly, it underscores the advancements our industry has made in *data infrastructure*. In composites manufacturing, data infrastructure is the means by which design and manufacturing data are communicated to the workcell to guide and monitor fabrication of actual components. As more automation enters the fabrication process, new data infrastructure is required to guide that automation. Importantly, I believe, only those companies that build out their data infrastructure will be able to take full advantage of the automation technologies that are driving composites fabrication to new levels of efficiency and quality. This is true of automation technologies ranging from those that assist hand layup to those that complete entire fabrication processes.

Those mylar and fiberglass templates of the 1980s intermediated between the virtual CAD realm and the real world of component fabrication. Shaped to match a specific 3D pattern in a ply schedule, each template had to be lifted into place, carefully aligned and pinned to the tool. An operator then scribed the template's outline. After removing the template, the operator could then lay up the ply. This sequence was repeated for each ply — often hundreds of times to build one component. Both painstaking and inflexible, this fabrication process also pitted throughput against quality; that is, raising the manufacturing rate almost inevitably reduced component quality.

In the 1990s and early 2000s, the first data infrastructure elements lopped months or years off product development cycles, and days or weeks off manufacturing cycle times. Simultaneously, they improved the quality and consistency of composite components. Directly accessing and using design and manufacturing data, 3D industrial laser projection systems (which Aligned Vision introduced in 1988) replaced physical templates with "templates of light." Serving as data infrastructure, these laser templating systems communicated data in a useful form to the fabrication workcell. Inspectors also gained valuable help, because laser projectors could display nominal edge locations, fiber orientations and other ply features. However, data flowed in only one direction through this infrastructure; inspector stamps or initials were the only information coming back from the as-built component.

Starting in the early 2010s, data began to flow back from the component, as more data infrastructure eliminated time-consuming alignment of the templating system in automated workcells, such as automated fiber placement (AFP) systems. Partnering with laser projection providers, makers of automated workcells employ a software development kit (SDK) to fully integrate laser projection. The integrated system uses manufacturing data to automatically calculate the position of each point on the workpiece relative to the laser projector, thus keeping the projection system aligned even when an asymmetrical part is translated or rotated along different axes. In this application, a second party — the workcell developer — contributes to the data infrastructure.

With the recent introduction of automatic inspection systems, yet another party — the fabricator — now can play a vital role in data infrastructure development. Aligned Vision, for example, began developing automatic inspection in 2000, with automatic ply verification (APV), which verified and documented flight-critical characteristics on spars and skins. APV marked the beginnings of bi-directional data infrastructure, automatically generating quantitative quality data from the shop floor.

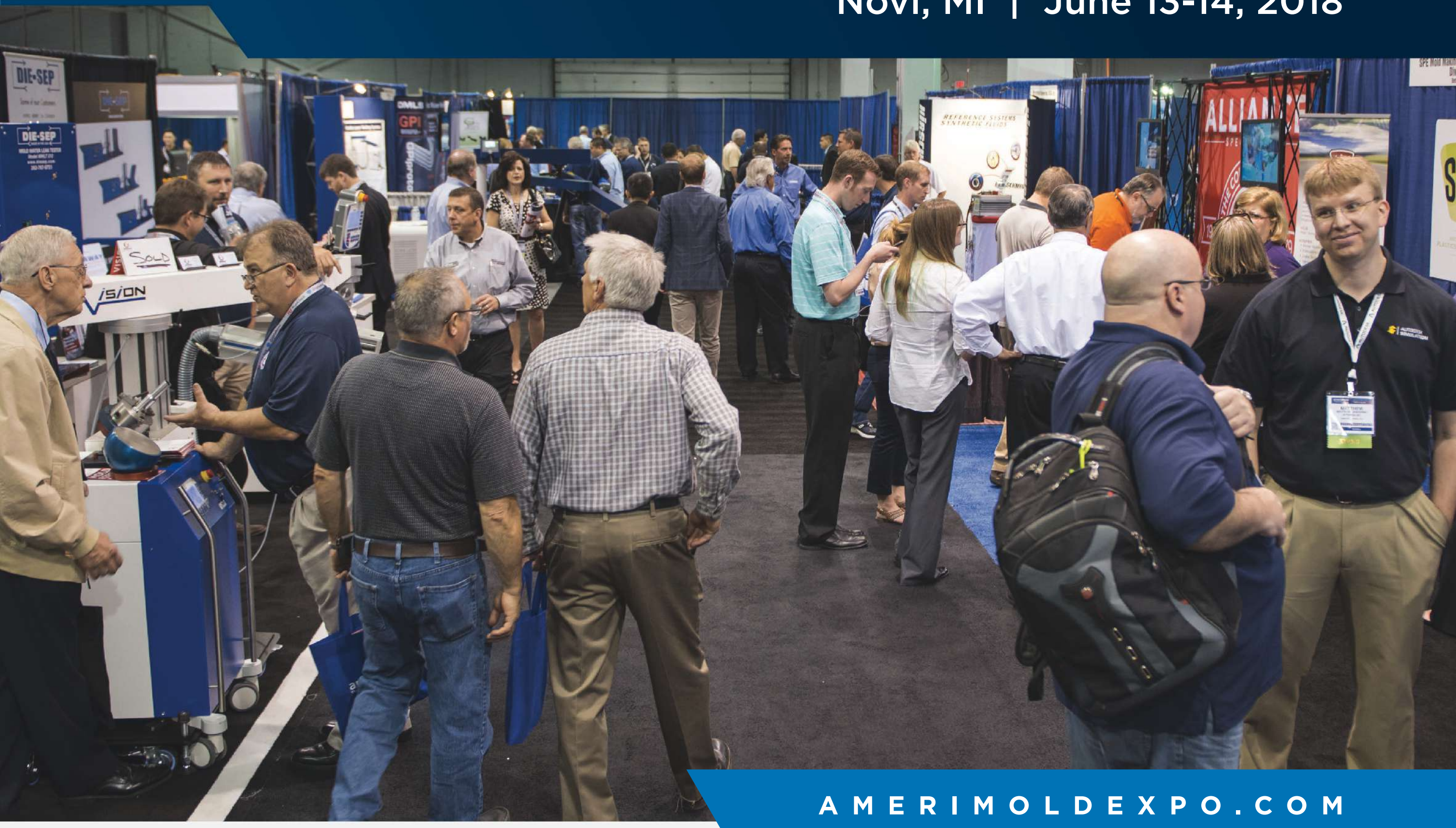
Today, Aligned Vision's automatic inspection systems incorporate a laser projector and a high-magnification, high-resolution camera. The camera captures detailed images that may include laser reference lines, and the laser projector pinpoints out-of-tolerance features for rework. To analyze the captured images, the system uses analysis algorithms tailored to specific materials and component features. This is where the fabricator and inspection system provider must work closely together to equip the system with required information and programming (i.e., data infrastructure).

Automated inspection adds value to the fabrication process through accelerated, high-quality fabrication and through full traceability provided by as-built electronic documentation. Yet the value-adding capacity of automatic inspection is still in its infancy. The next advancement in data infrastructure will feed inspection data to Smart Factory technology, which will enable fabricators to quickly detect opportunities and implement process improvements. For example, the automatic acquisition of as-built fiber orientations in first articles will enable analysis of actual part parameters rather than the nominal, thus decreasing the need for overdesign to account for manufacturing variation.

It is my observation that industries cannot optimize their processes and products unless they optimize their organization. In composites manufacturing, companies that progress toward implementation of Big Data — those that build out their data infrastructure — will move toward such optimization, and likely will be the big winners in our future marketplace. CW

ABOUT THE AUTHOR

Scott Blake is president of Aligned Vision (formerly Assembly Guidance, Chelmsford, MA, US). Among the leaders in 3D industrial laser projection, his company developed numerous industry "firsts," including multitasking laser systems, full workcell integration and automatic inspection. His work on the USAF's Composites Manufacturing Process Control System garnered him a 2000 National Tibbetts award.



To the Moon and Mars?

» Like millions of others around the globe, I watched the live Webcast on *YouTube* of the SpaceX *Falcon Heavy* launch on Feb. 6 with fixated interest. The rocket was designed with the largest thrust and payload capability since NASA's *Saturn V* rocket was retired in 1973 — we were witnessing a moment in history. Although the launch was originally scheduled for early afternoon, high-altitude winds halted the countdown, threatening to postpone the launch by a day. By no means was success guaranteed (it never is with rocket launches). In an interview with one of the US national networks, SpaceX founder and CEO Elon Musk cautiously offered a 50-75% probability that all would go well.

> CFRP will get us back to the Moon and on to Mars, but even more, will help us live well when we get there.

With just minutes to go before the day's launch window would close, the countdown resumed unabated, and *Falcon Heavy* left the launchpad, both side boosters disengaged and — spectacularly — returned to touch back down, perfectly upright on Earth-based landing pads, in a fashion that looked more like ballet than rocket science. Meanwhile, the center core continued upward, and delivered its test payload, Musk's red carbon fiber-bodied Tesla *Roadster,* into space, headed to an intended orbit of the sun near that of Mars. Despite the center core missing its landing on a drone platform at sea, this first launch was declared a success, paving the way for future, large-cargo missions.

SpaceX has managed this despite launching its first rocket less than 10 years ago. There is no question that Elon Musk is nothing if not unconventional and provocative, as I've written briefly about him in this column in January 2016. He's a definite risk-taker, as evidenced by the number of ventures he has started, most notably Tesla Motors, producer of battery-powered cars, and more recently, heavy trucks. To provide the batteries for its vehicles, as well as its in-home *Powerwall* storage systems, Tesla built a giant facility, named the *Gigafactory*, in Nevada, with plans for additional factories. Tesla also has introduced residential shingles that double as solar panels (feeding energy to their home storage systems), and Musk has launched both *Hyperloop* and The Boring Co. to speed up transportation within and between large cities.

With *Falcon Heavy*, Musk clearly has set his sights on establishing a colony on Mars, with the Moon as an intermediate base station, and on doing so within the next decade. This goal is supported by the current US administration's directive to NASA that it move forward with returning humans to the Moon, and eventually, sending humans to Mars.

SpaceX is not the only rocket company sensing opportunity in this arena. Boeing, Lockheed Martin and Blue Origin, founded by Amazon's Jeff Bezos, also are working on heavy launch vehicles that are able to deliver big payloads into deep space.

Irrespective of what launch vehicles provide transport for colonization efforts to the Moon or Mars, advanced composites are sure to play an enabling role. Although only the interstages and payload fairing of the *Falcon 9* and *Falcon Heavy* are composites, it is the *payloads themselves* that these and other rockets will carry that matter most. For decades, satellites, probes and space telescopes have relied on lightweight carbon fiber composites to achieve their missions and allow extra fuel and instruments to be carried aboard.

The *strength-to-weight* and *stiffness-to-weight* ratios of carbon fiber composites compared to metals make them essential to effectively setting up bases on the Moon and Mars. Limits on payload capability are defined by the thrust needed to overcome Earth's gravitational pull. By using lower-density materials like composites, more building materials needed to establish base structures can be sent with each mission. Speaking of gravity, that force on the Moon is only one-sixth that on Earth. On Mars, it's just over one-third vs. Earth. Although such structures will have the same mass as on Earth, the supported *weight*, which is proportional to the force of gravity, will be much lower, further enabling lighter structures. Of course, any buildings erected on these distant orbs will need to withstand other environmental forces, such as wind, erosion and impacts. Who says everything must be sent to space already fabricated? Common elements, like composite sheets, rods and tubes, which can be packed neatly, make sense to fabricate down here. But such missions offer opportunities for novel composite materials and technologies. Why not send up several 3D printers along with containers of carbon fiber-reinforced polymers, and just *fabricate* connectors, vehicle components and other items onsite? Surface transportation is most likely to be battery-powered, and lightweight vehicles made of advanced composites produced via 3D printing make perfect sense. Whether such vehicles will look at all like a Tesla *Roadster* is still anyone's guess. 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.

Gripping composite test specimens: Options and guidance

» Regardless of the type of mechanical test being performed on composite materials, load introduction into the test specimen is among the biggest challenges. Fiber-reinforced composites have relatively high strengths when loaded in the fiber direction and, thus, relatively high forces must be transferred into the test specimen. However, unidirectional fiber-reinforced composites also have relatively low strengths when loaded in other orientations. This orthotropic material behavior — having different strength properties in different directions— makes load introduction even more problematic. Isotropic materials, such as metals and plastics, have the same strength in all directions. But the tensile strength of a carbon fiber composite, for example, is typically 20-30 times higher in the fiber direction than in the perpendicular direction. The shear strengths of unidirectional composites are relatively low as well.

Orthotropic behavior of composites test specimens makes load introduction uniquely challenging.

The high fiber-direction strength and orthotropic material behavior of composites often preclude the use of specimen designs and methods of load introduction developed for use in testing metals and plastics. Consider, for example, the flat dog bone-shaped specimen that's commonly used for tension testing (Fig. 1a, this page). The specimen's wider ends provide increased surface area for gripping and shear loading. The reduced cross-sectional area in the central region introduces higher tensile stresses that result in desirable test section failures. However, if this same concept is used with unidirectional composites, longitudinal splitting will occur, which effectively produces a straight-sided specimen (Fig. 1b). The reason? High shear stresses are produced in the width-tapering regions and unidirectional composites have low shear strengths.

For tensile testing unidirectional composites, end tabs typically are bonded to the top and bottom specimen surfaces in the gripping regions (Fig. 1c) to produce a greater cross-sectional area than in the central test section. The relatively large surface area of the bonded tab produces lower shear stresses, and the desired test section failures. Bonded tabs also provide a sacrificial outer layer that can be gripped without damaging the outer layers of the composite. Glass fabric/epoxy laminated circuit board material is most commonly used for tabbing. Guidelines for tabbed tensile specimen design and testing are provided in ASTM D3039[1].

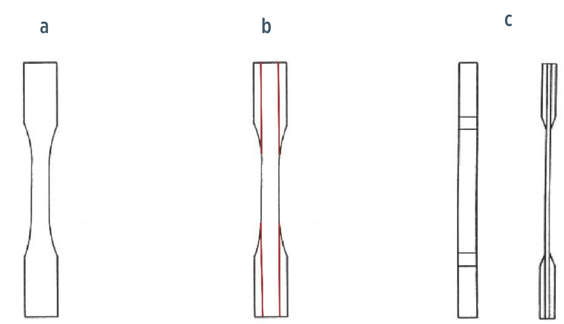


FIG. 1 Composite tensile specimen design

Fig. 1a: Dog bone-shaped tensile specimen
Fig. 1b: Longitudinal splitting of composite dog bone specimen
Fig. 1c: Tabbed composite tensile specimen

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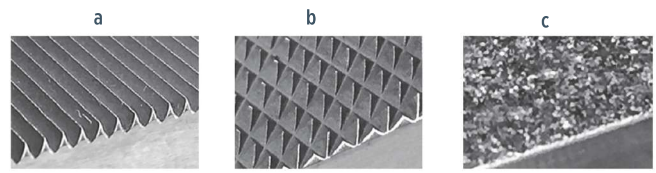

FIG. 2 Grip surfaces used for composites

Fig. 2a: Straight serrations
Fig. 2b: Crosshatched serrations
Fig. 2c: Particle-coated

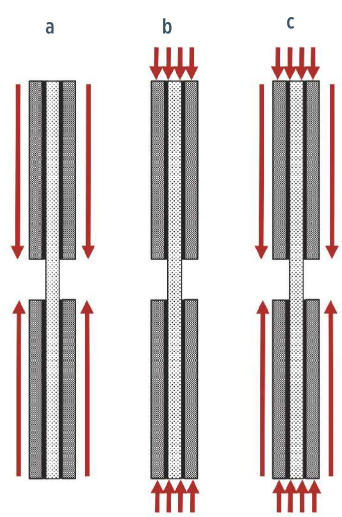

FIG. 3 Load introduction methods for compression testing

Fig. 3a: Shear loading
Fig. 3b: End loading
Fig. 3c: Combined loading

Gripping of tabbed composite tensile specimens typically is performed using mechanical or hydraulic wedge grips. The 10-15° wedge angle on the grip inserts produces a clamping force that increases proportionally with the tensile force applied by the testing machine. Due to the variety of gripping requirements produced by composite specimens of different strengths and thicknesses, a variety of grip surfaces are commonly used. The greatest load introduction is achieved using straight serrations (Fig. 2a, p. 10), which bite more deeply into the gripped surfaces. They're also useful for accommodating surface irregularities. Cross-hatched serrations, typically machined in a diamond pattern (Fig. 2b), are less aggressive but permit high load introduction when the gripped surfaces are not too irregular. For cases of reduced load introduction requirements and for relatively flat and smooth specimen surfaces, tungsten carbide particle-coated gripping surfaces (Fig 2c) in the range of 60- to 100-grit may be used. These surfaces minimize damage to the gripped surfaces and for that reason, in some cases, allow the use of untabbed specimens. Additionally, the use of unbonded friction tabs may be feasible for cases of reduced load introduction requirements. In this case, medium-grit emery cloth (with the grit-side toward the specimen) may be used with less aggressive wedge grip surfaces. When the gripping options are limited to more aggressive grip surfaces, such as straight serrations, butyrate plastic strips placed against the grip serrations followed by drywall sanding screen has been a successful strategy in cases of reduced load introduction. In any case, the abrasive layer must be able to withstand the compression and shear forces produced during gripping.

Compression testing requires similar adaptations and offers some additional challenges for load introduction into composite specimens. Like tensile specimens, compression specimens may be tabbed and shear-loaded through the tabbing surfaces (Fig. 3a, p. 10). The most commonly used shear-loaded compression test method, ASTM D3410[2], uses straight serrations on the test fixture's wedge grip surfaces for load introduction. Additionally, compression specimens may be end loaded (Fig. 3b). For many composites, bonded tabs are required to avoid crushing or splaying at the specimen ends prior to the desired compression failure in the central test section. The bonded tabs serve to increase the load-bearing area of the specimen ends, and the compressive forces introduced into the specimen tabs are transferred into the composite specimen via shear stresses along the lengths of the tabbed sections. The Modified ASTM D695[3] test and the SACMA SRM 1R-94[4] test are commonly used end-loaded compression test methods. »

A third method of load introduction for composite compression specimens combines shear loading and end loading (Fig. 3b, p. 10). For this combined loading compression testing, it is desirable to introduce as much load as possible directly into the ends of the composite specimen without failure at the specimen ends. The remaining load introduction is obtained by shear-loading the specimen surfaces. The combined loading compression (CLC) test method, ASTM D6641[5], is one of the most commonly used compression test method for composites. The specimen-gripping surfaces of the test fixture are coated with tungsten carbide particles for shear loading. A combination of end loading and shear loading is sufficient for compression testing many woven fabric-reinforced materials and 0°/90° cross-ply composite laminates without the use of bonded tabs. However, bonded tabs are required for successful compression testing of most high-strength unidirectional composites.

One method of reducing the load introduction requirements for both tensile and compressive testing is by decreasing the specimen thickness. Unlike tensile testing, however, the thickness of compression specimens must be sufficient to prevent buckling from occurring during the test. In general, a thicker specimen and considerably shorter test section are needed when compression testing. Typically, the shortest practical test section length is selected, and the required minimum specimen thickness to prevent buckling is determined. CW

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Dr. Daniel O. Adams is a professor of mechanical engineering and has been the director for 21 years of the Composite Mechanics Laboratory at the University of Utah and vice president of Wyoming Test Fixtures Inc. (Salt Lake City, UT, US). He holds a BS in mechanical engineering and an MS and Ph.D in engineering mechanics. Adams has a combined 38 years of academic/industry experience in the composite materials field. He has published more than 120 technical papers, is vice-chair of ASTM Committee D30 on Composite Materials and co-chair of the Testing Committee for the *Composite Materials Handbook (CMH-17)*. He regularly provides testing seminars and consulting services to the composites industry.

The US composites industry's rally continues in February

February 2018 – 59.6

» Registering 59.6 for February, the Gardner Business Index (GBI): Composites Fabricating extended its healthy business expansion rally for a third month. The February reading set a new all-time high for the Index, which was first recorded in 2011. The previous high was hit in October 2017.

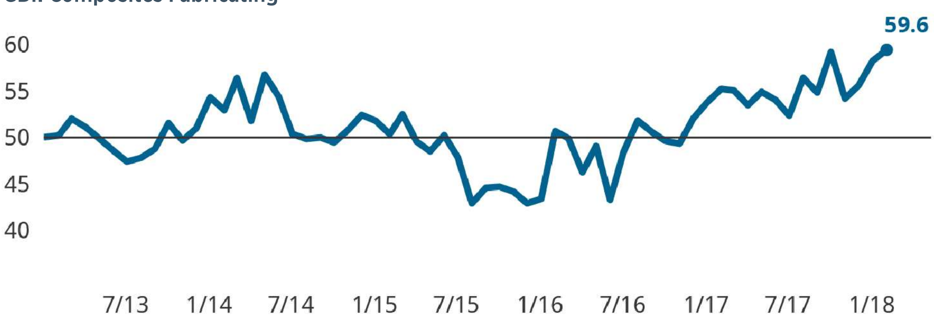
Compared to the same month one year earlier, the February 2018 Index had increased approximately 7.3 points. A review of the underlying data for the month by the Gardner Intelligence team indicates that the Production and New Orders subindices lifted the Index higher while Supplier Deliveries, Backlogs, Employment, and Exports tended to hold the Index reading down. That said, for a second consecutive month, no Index components in February indicated contraction (registered <50.0) during the month.

The readings for Production and New Orders grew in February at a rate that has rarely been seen in the history of the Index. The only other times when these measures have expanded as quickly were in the first quarter of 2012 and in the second quarter of 2014. While the data indicate that Production is keeping pace with the strong growth of New Orders, Backlogs nevertheless continue to grow, according to survey respondents. Exports readings, since the fourth quarter of 2017, have recorded their best overall performance in the history of the Index. 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**

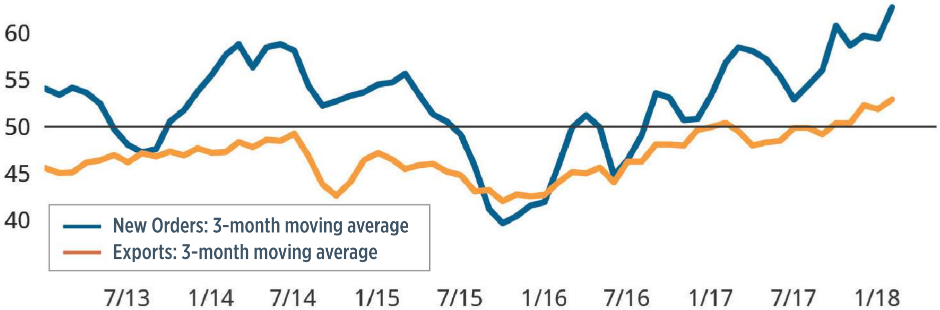
GBI: Composites Fabricating



Expansion in all Index categories

The Composites Fabricating Index reading closed out February at a new all-time high. Production and New Orders have been the essential drivers, according to survey participants. All six measured components of the Composites Fabricating Index showed expansion (>50.0) during the month.

GBI: Composites Fabrication - New Orders and Exports



Index trends indicate a prosperous 2018

Since the fourth quarter of 2017, New Orders expansion has originated from both domestic and international consumers of composites products. As fabricators have increased Production, Backlogs also have continued to grow. Gardner Intelligence sees in these trends a very good year for US composites fabricators in 2018.

An excerpt from the *CW Talks* interview with *CW's* own Donna Dawson, research into the impact of epoxies and polyurethanes on part shrinkage and surface quality, and a look at efforts to recycle end-of-life wind turbine blades.

Q&A: Donna Dawson, *CW* contributor, composites veteran

CW contributor Donna Dawson has been writing for the magazine for almost 20 years. Prior to that, she built a long and storied career working with Brandt Goldsworthy, one of the composites industry's pioneers in manufacturing process development. Donna started as a secretary to Goldsworthy in the 1960s and eventually became a technical specialist. Donna sat down recently with CW Talks: The Composites Podcast *for a trip down the composites memory lane. That interview is excerpted here. You can listen to the entire discussion at www.compositesworld.com/podcast, or you can listen on the* CW Talks *podcast on iTunes or Google Play.*

***CW*: What was it like working with Brandt Goldsworthy?**

DD: At first, I would drive up to his house in the evening and take dictation by shorthand, and his wife and family would try to live quietly around us. He always needed everything yesterday and so I would go back to my home office and send him the finished documents as soon as I could, by real mail at that time. It was an entirely new language for me, and a challenge finding shorthand squiggles for 'catalyst,' 'filament winding,' 'pultrusion' — it was fun and exciting. .... I was learning the language and more about the technology every day. The language then, I might note — was not composites, it was fiber-reinforced plastics, and not composites manufacturing but FRP fabrication. It was mostly fiberglass and polyester or vinyl ester resins.

***CW*: Tell us some of your memories of innovations you witnessed.**

DD: His primary efforts then were negotiating with Ferro Corporation, in Nashville, to start up a new company for designing and building automated equipment for processing fiber-reinforced plastics. That did come to pass, they did negotiate that, and I became one of the first four employees as secretary of the Goldsworthy Engineering Div. of Ferro Corporation. .... The others were Brandt, Denny Franks, mechanical engineer, and Bill Johnson, electrical engineer. .... And later, E.E. Hardesty, called 'Tiny' because he was so big, joined us. It was really a great crew. Working with those creative people — it was exciting to go to work each day.

***CW*: How did Goldsworthy go about trying to automate some of these processes?**

DD: That was his mantra, to automate the industry. To take the industry from hand layup to automated production, and he did a very good job of it, designing and building new filament winders, pultrusion machines, tape placement, fiber placement. .... We contracted with Thiokol to build the first winding machine that used a numerical punch tape control and its purpose was to wind a casing over solid rocket propellant. At that time, early computers were not equal to the programming job. There was a single Thiokol engineer and his first name was Jim — I don't remember his last name — he spent hours studying the job spec and programming the critical punch tape program. No computer, finite element analysis, no computer modeling, just Jim and his slide rule and calculator working through the night.

***CW*: What else do you remember?**

DD: Ferro eventually closed the Goldsworthy facility. ... The company was soon reborn as the Goldsworthy Engineering Div. of Monsanto. .... One big job was with Bob Werner, of Werner Brothers in Greenville, Pennsylvania, now Warner Company. We were developing continuously pultruded fiberglass ladder rails for them. I came to work one morning to find a continuous rail had been pultruded through the shop, out the window, in through the front door and up the stairs, and an empty bottle of champagne sat on my desk. Ladders with fiberglass rails are standard for any work around electricity today. It amazes me when I see how common they are ... and to remember I was there in the beginning.

***CW*: You left Goldsworthy for a while to go to college and returned as a technical writer, writing operating manuals. What was that like?**

DD: I learned to read the drawings and I'd work with the engineers on the design and then write up how it works, how to operate the machine and do machine maintenance. And when the machine builders in the shop told me I had written a good manual, I felt like I had succeeded. ... Around the late 1980s, Brandt sold the company .... We got a contract from Forest Liné in France at that time for a two-stage automated tape layup system, the ACCESS ATLAS V. The concept was developed as a solution to problems with automated tape layup when that technology was just getting started. The head would lay continuous tape to the end of the path and cut and turn around to go back. But even if one little string didn't cut, it would tear up the previous layup. Goldsworthy's solution was to precut plies in the first stage and then lay them in the second stage. …. The system is now owned by Fives in France and a slightly modified version of that system is being used by Mitsubishi Heavy Industries in Tokyo to build wingskins for Boeing 787 *Dreamliners*.

***CW*: What's your take on where the industry might go?**

DD: Some top technologies that are, and I believe will be, winners are curved pultrusion, which I did an article on last year … and thin ply tape, where they take the tow and spread it out and it becomes very thin and very light weight. It's an enabler for some extremely lightweight products — for example, one-piece carbon fiber sails and the *Solar Impulse* solar-powered aircraft that flew around the world. Ceramic-matrix composites, I think, have a great future in aircraft engines. …. And out-of-autoclave processing, for some applications, seems like it will be a really good process decision. But I think the real heroes of composites are the material developers. …. and the processing people, too, the manufacturers. …. They seem able to respond to anything.

BIZ BRIEF

Following several years of close technical collaboration, **ELG Carbon Fibre** (Coseley, West Midlands, UK), a market leader in recycled carbon fiber materials, and **Sanko Engineering and Tooling (SET)** and **Sanko Gosei UK** (Lancashire, UK) announced Feb. 15 that they have formalized their commercial partnership. A key element of this strategic alliance will be the further development of cost-effective, lightweight materials processing solutions which can be marketed to composite component manufacturers in the automotive market.

SET and Sanko Gosei reportedly have developed innovative design solutions that take advantage of the greater performance benefits that can be obtained from polymers reinforced with ELG's recycled carbon fiber. This combination of technologies has facilitated the extension of injection molded plastics into automotive structural applications, providing significant weight savings compared with other reinforced plastic materials or metals.

SET's manufacturing expertise and advanced tooling concepts are said to enable complex and high-quality structural parts to be manufactured with cycle times under one minute.

Source | Evonik

Evonik resin research targets surface quality, shrinkage control

A new white paper from Evonik Resource Efficiency GmbH (Marl, Germany), authored by Eike Langkabel, Sebastian de Nardo and Jens Bockhoff, examines the best resin formulations for composites used in automotive part production, both structural parts and body panels. Specifically, the report takes a deep dive into the behavior of various curatives and their effects on resin shrinkage, and compares epoxy and polyurethane formulations.

Residual stress is a significant problem in composites processing, say the authors, caused by chemical shrinkage of the matrix due to crosslinking of molecules, mismatch of thermal expansion or contraction among fibers and matrix (a cause of fiber print-through) and viscoelastic relaxation during fabrication. These phenomena are strongly coupled, and can lead to defects in the finished part, including shape distortion, micro-cracking, delamination, reduced mechanical strength, wavy surfaces and aging. And, for automotive composites, resin systems face conflicting demands, for fast cycle times on the one hand, which can produce residual stress, and Class-A surface quality on the other hand, which decreases with increasing stress.

First, the researchers cured samples of a variety of epoxies, using a bisphenol A diglycidyl ether (DGEBA) cured with isophorone diamine. Using a variety of test methods, including volume diatometry, DIN EN ISO 3521 (Pyknometer/Buoyancy Scale) and the pVT method (developed by RWTH Aachen University, Aachen, Germany), the overall shrinkage behavior of the epoxy was determined to be 2.3-2.4%. Then, using thermomechanical analysis (TMA), changes in length were measured in epoxy samples. The results indicated that changes in dimension (shrinkage/expansion) are due to relaxation processes and the release of "frozen-in" free volume within the samples.

More tests were run using a range of reactive amines, the curing agents used in epoxy processing. Samples were created with cycloaliphatic, araliphatic and aliphatic amines, to determine their effects on shrinkage, and a variety of reactive diluents were also investigated, with the samples cured for 30 minutes at 120°C. The cycloaliphatic structures showed the lowest shrinkage (2.4%), while aliphatic structures show higher shrinkage. The longer the aliphatic chain length, the higher the shrinkage. And, the longer the aliphatic chain length (higher mobility) of the reactive thinners, the more shrinkage was observed, up to 4.5%.

In the final part of the study, composite parts were produced using the resin transfer molding (RTM) process, to enable observation of shrinkage and resulting part surface quality. Parts were made with the same fiber architecture, a quasi-isotropic layup using non-crimp fabrics, and were cured for 10 minutes at 120°C. The results verified that an epoxy resin formulation containing cycloaliphatic structures was superior to highly formulated resin systems that contain open-chain aliphatic components, and produced a part with very little surface waviness, particularly when the part was made with an additional in-mold coating (IMC), using the same resin formulation.

To further reduce shrinkage effects, the authors suggest the use of a polyurethane prepreg. Evonik's polyurethane system, VESTANAT PP, based on aliphatic diisocyanate with a uretdione structure, cures quickly while still offering good mechanical properties and high toughness, and is stable with room-temperature storage. Because it behaves like a thermoplastic before cure, in its prepolymer state, it can be easily preformed, yet after cure it has thermoset properties. In terms of shrinkage, the paper compares epoxy cured with cycloaliphatic amine (IPD/DGEBA system, 2.4% shrinkage) to VESTANAT PP resin, which exhibited less than 1% shrinkage, attributed to the chemistry and process differences.

The authors showed that using polyurethane prepreg in a simple PCM (prepreg compression molding) process yields parts with surface qualities in the same range as the optimized epoxy formulations, while noting that surface properties in general are also linked to the fabrication process, the fiber architecture and the integrated surface finishing technologies (i.e., IMC) used.

The technical paper is available in PDF format on the *CW* Web site | **short.compositesworld.com/EvonikPpr**

BIZ BRIEF

LyondellBasell (Rottedam, The Netherlands and Auburn Hiills, MI, US) one of the world's largest plastics, chemicals and refining companies, and **A. Schulman Inc.** (Fairlawn, OH, US) a leading global supplier of high-performance plastic compounds, composites and powders, announced Feb. 15 that they have entered into a definitive agreement under which the former will acquire the latter for a total consideration of US$2.25 billion. The acquisition is expected to broaden LyondellBasell's geographic reach and extend its already a diverse product portfolio. "The acquisition ... will allow us to provide our customers with a wider range of innovative solutions while adding the ability to serve high-growth end markets beyond the automotive sector, such as packaging and consumer products, electronics and appliances, building and construction, and agriculture," says Bob Patel, CEO of LyondellBasell.

ENERGY

Global team explores reuse of wind turbine blades

Wind energy technology has grown rapidly, worldwide, over the past 15 years. Given the approximate 20- to 25-year useful life of the non-biodegradable rotor blades in current wind turbines, many will need to be replaced in the near future. Researchers in the US, the Republic of Ireland, and Northern Ireland are collaborating on a blade reuse project, developing a sustainable approach that benefits local communities and sets a new course for the wind energy industry that replaces the unsustainable disposal methods of landfilling and incineration. The project will explore the blades' potential reuse in architectural and engineering structures. Such methods can have a positive effect on air quality and water quality, decreasing a major source of non-biodegradable waste.


Source | RE-WIND

Called RE-WIND, the project is funded under the US-Ireland Tripartite Research Program (Dublin, Ireland). Team members span the disciplines of engineering, architecture, geography, sociology and political science. Project leaders and participating schools are Lawrence Bank, adjunct professor at the Grove School of Engineering at City College of New York; Russell Gentry, professor of architecture and civil engineering at the Georgia Institute of Technology; Paul Leahy, lecturer in wind energy engineering at University College Cork; and Jian Fei Chen, professor of civil and structural engineering at Queen's University Belfast.

Bank says the research will provide valuable information about wind energy not only to energy and waste-management policymakers, wind energy company executives and wind turbine manufacturers and installers but also to concerned community members: "The methodology we create in this research could be applicable to other large manufacturing industries," adds Bank.

Ireland is the testing ground because it offers great geographical/social contrast — from coastal to mountainous, with urban, suburban and rural communities — in a relatively compact space. At the recent project kickoff meeting in Cork, advisory board member Jeffrey Russell of the University of Wisconsin-Madison (US) conducted a master class in project leadership to address the unique challenges of managing a globally distributed team. Other advisory board members in attendance were John Blaho, director for industrial/academic research at City University of New York; and Nathan Post, lead engineer at WindESCo (Boston, MA, US), a technology company specializing in wind energy.

"Wind power is an increasingly important renewable energy source," says Bank. "If we can find a socially acceptable reuse and recycling method for the non-biodegradable materials in wind turbine blades, we can make a significant contribution to its development."

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**

Toray acquires TenCate Advanced Composites
Toray, the world's largest carbon fiber manufacturer, will pay €930 million (>US$1.15 billion) for TenCate to shore up its thermoplastic composites capabilities.
03/14/18 | short.compositesworld.com/TorayTAC

NIAR establishes engineering design and modification team
The team comprises 35 engineering consultants previously employed by the Bombardier Flight Test Center in Wichita, KS, US).
03/14/18 | short.compositesworld.com/NIAR-EDMT

BMW Concept *M8 Gran Coupe* features CFRP roof
New *M* variant concept car, featuring a carbon-fiber-reinforced-plastic roof, shows off BMW's new design language.
03/09/18 | short.compositesworld.com/M8Roof

Airborne announces composites manufacturing partnerships
At JEC World 2018, Airborne unveiled numerous business partnership plans for automated honeycomb potting and cutting/kitting solutions.
03/09/18 | short.compositesworld.com/AirborneP

Bally Ribbon Mills launches line of woven webbing for aerospace applications
Fabrics can meet the specific strength requirements of structural components.
03/08/18 | short.compositesworld.com/BallyWeb

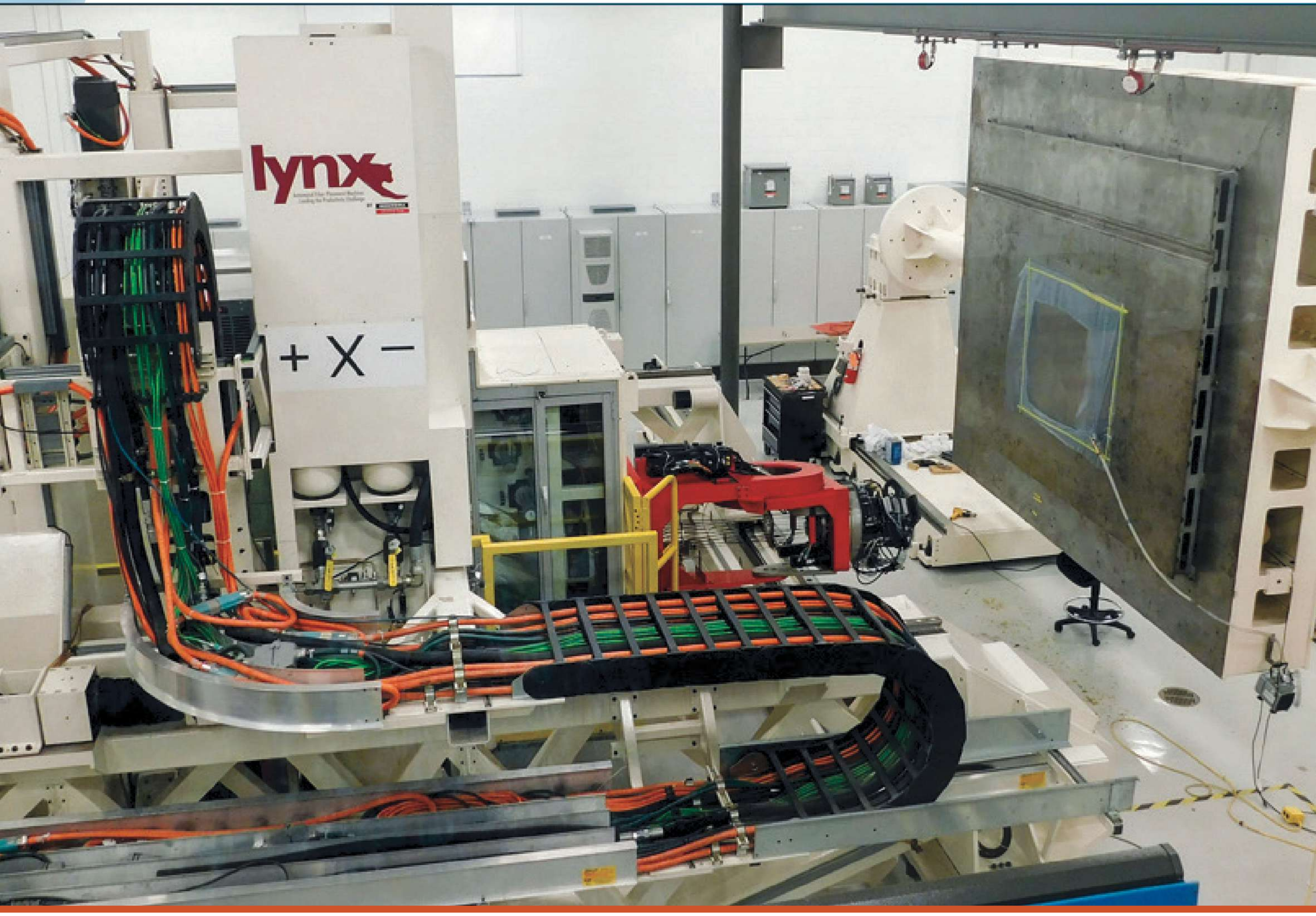
Composites One and IACMI partner for Road2Composites workshop
"Road2Composites: Scaling Up Innovation," an automotive-themed workshop, will be presented April 17-18 in Detroit, MI, US.
03/08/18 | short.compositesworld.com/Road2Comp

Michelman to partner with AZL Aachen GmbH
Michelman's latest move is part of its partnership strategy to further advance and improve composite development throughout the industry.
03/07/18 | short.compositesworld.com/MichelAZL

John Deere to acquire carbon fiber composite manufacturer King Agro
Deere & Company has signed a definitive agreement to acquire the privately held supplier of its CFRP agricultural boom sprayer equipment.
03/07/18 | short.compositesworld.com/DeereKA

Renault Sport Formula One Team announces relationship with Plataine
Plataine was selected due to its proficiency in the latest Industrial IoT and artificial intelligence technologies applied to composites manufacturing.
03/06/18 | short.compositesworld.com/RSF1-Plat

Dolphitech ultrasound camera system accepted by Airbus
A nondestructive testing procedure for the Dolphicam ultrasound camera system has been made available for the Airbus A350 composite aircraft.
03/06/18 | short.compositesworld.com/DolphiAB



McNair Aerospace Center: Closing the composites education gap

As the composites industry in South Carolina continues to expand through Boeing and its tier suppliers, composites education follows suit through the McNair Center.

By Karen Mason / Contributing Writer

FIG. 1 Largest AFP in a US research university

Similar to machines used on the production floor at The Boeing Co.'s (Chicago, IL, US) plant in South Carolina, this Lynx automated fiber placement (AFP) equipment, supplied by Ingersoll Machine Tools Inc. (Rockford, IL, US), gives the McNair Center a production-level system on which to build test articles and prototypes. Source | McNair Center

» Although expanding investments in South Carolina's developing aerospace industry by The Boeing Co. (Chicago, IL, US) regularly capture regional and composites industry headlines, one of the state's major educational institutions is more quietly, yet resolutely, making significant investments in aerocomposites workforce development. Composites technology is central to all four areas of focus listed in the mission statement of the University of South Carolina's (USC's) Ronald E. McNair Center for Aerospace Innovation and Research (Columbia, SC, US): aerospace education, research, outreach and economic growth. From course work as diverse as science, technology, engineering and mathematics (STEM) outreach to CATIA certification classes and core research into steered fiber laminate design, the McNair Center has set out to address the needs of the aerospace composites workforce at not only professional and collegiate levels, but also in K-12 educational institutions as well.

Named after South Carolina native and *Challenger* Space Shuttle astronaut Ronald McNair, the Center was founded in 2011 expressly in response to Boeing's investment in South Carolina. USC previously had offered only an aerospace minor in its mechanical engineering program. Expansion of aerospace research and studies has occurred through the McNair Center endowment, funded by South Carolina philanthropists Darla Moore, Anita Zucker and Marva Small, all three of whom "are especially interested in workforce development," notes center director Michel van Tooren. So far, McNair Center efforts have enabled the creation of two master's degree programs: an MS in aerospace engineering and an ME in aerospace engineering.

A bachelor of science program in aerospace engineering is expected to open in fall 2018, van Tooren reports. It will offer 15 aerospace-intensive courses. Students will choose from three tracks in the program, one of which focuses on aeromechanical systems, where composites technology plays a predominant role. (The other tracks focus on aircraft electrical systems and air-related information technologies.) Next, the Center faculty hopes to modify and amend the existing program, which currently awards a Ph.D in mechanical engineering, to confer in future a Ph.D in mechanical and aerospace engineering.

Practical academics

Van Tooren came to McNair in 2013 after previously held positions in The Netherlands, involving academic research at Delft University of Technology (Delft) and industrial research at Fokker Aerostructures (Papendrecht). He and many of his fellow faculty members continue to conduct research that bridges academia and industry, and this emphasis at the Center has produced an atmosphere of practical, industry-focused exploration.

For example, Subramani "Mani" Sockalingam, a recent addition to the McNair faculty, worked in composite body armor product development before pursuing his Ph.D at the University of Delaware Center for Composite Materials (Newark, DE, US). His current research uses FEM and FEA tools to study the constituents and interfaces within composite materials. But even this fundamental research is conducted with an eye toward application. Sockalingam is lending his micro-scale expertise to a McNair team that is working on induction welding of composites. This interplay between basic and applications research advances »

FIG. 2 Emphasis on practical, not just theoretical, education

The McNair Center's autoclave, oven and other production equipment give students hands-on experience with composites manufacture.

Source | McNair Center

both, Sockalingam believes, citing two projects that are studying joint reliability: An induction welding project emphasizes structural performance, while a complementary basic research project is studying joints from a molecular dynamics perspective.

The McNair Center's 30+ faculty members represent mechanical, chemical, civil and electrical engineering disciplines. This multidisciplinary approach applied to composite aircraft structures means that the Center can cover the full spectrum of research: design, modeling, manufacturing and analysis. Ph.D candidate Jaspreet "Jessie" Pandher has found that multidisciplinary collaboration, plus access to shared equipment and exposure and connections to industry, are assets of Center-based research not often enjoyed by either traditional academic or industry-based research.

Although he initially entered USC to study mechanical engineering, Pandher "fell in love with aerospace" through an internship at the Center. He worked on an industry-sponsored UAV development project before beginning his Ph.D work. "It's unique that we get to do actual industry projects that are going to be used by the industry sponsor," he says. Within the Center, he adds, "Everyone is open to help out; you're not secluded in one group."

Center interns can benefit from working on projects that contribute to real commercial ventures.

Industrial collaboration and equipment

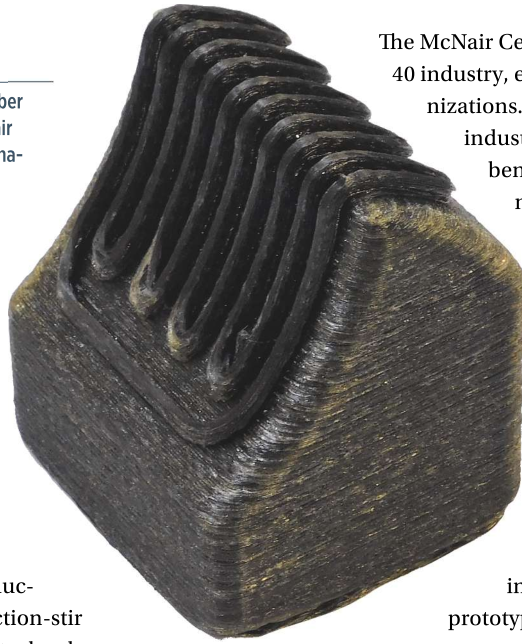
A tour of the McNair Center evidences the industrial, hands-on orientation of the work there. One centerpiece is the Lynx Fiber Placement Machine from Ingersoll Machine Tools Inc. (Rockford, IL, US), reportedly the largest AFP machine in a US research university (Fig. 1, p. 20). Able to lay down 16 0.25-inch/6.45-mm tows per pass, this production-level machine is producing test articles for the center's exploration of an unconventional steered-fiber laminate design (see Learn More, p. 25), as well as dry fiber placement using HiTape unidirectional reinforcements from Hexcel Corp. (Stamford, CT, US). As test articles are fabricated on the AFP machine, a head-mounted Ingersoll profilometer collects inspection data and the system analyzes actual fiber placement. Any flaws (e.g., twisted or missing tows, foreign objects or debris) are highlighted by a LASERGUIDE laser projection system (Aligned Vision, Chelmsford, MA, US), enabling immediate error correction.

Fiber steering is a focal point of McNair Center research, and equipment like the Lynx system enables a design-for-manufacture orientation, points out Darun Barazanchy, a post-doctoral researcher. Barazanchy is performing interlaminar shear research to develop optimized paths for fiber steering. He says that his research benefits from the fact that the Center is fully equipped for fabrication (Fig. 2, p. 22): "We can actually build it. We can do our predictions, optimize the design, manufacture and actually test it."

"You can see how hard it is to move from paper or software to an actual panel," he continues. "In the simulation world, you may see that something is optimum, but is it optimum in manufacturing?" As part of his research, Barazanchy is identifying the »

FIG. 3 Research: Additive manufacturing of composites

This test article was produced with a 3D continuous-fiber printing process, now under development at the McNair Center, just one example of the Center's effort to emphasize research into processes and product outcomes on the cutting edge in terms of commercial interest and practicality. Source | McNair Center



ways in which certain manufacturing parameters affect performance. These include not only more obvious factors, such as tow width, but also the less obvious, such as the fabrication starting point — whether the AFP starts at one side or the other, or in the center of the tool.

Also central to research at McNair, a fusion bonding laboratory supports the induction welding project, as well as VARTM, friction-stir welding, and other fusion-based assembly technologies. Other McNair facilities support advanced composite material systems, using plasma treatments and grafting; nanoparticle-based interlaminar interface improvements; and 3D printing of continuous fiber-reinforced parts (Fig. 3, above right).

The McNair Center currently partners with nearly 40 industry, educational and government organizations. The Center's work with composites industry companies has proven mutually beneficial. The latter provide equipment and personnel who help McNair students use it to develop practical knowledge and skills, and aid the Center as it advances innovative technological developments to the brink of commercial applicability — at which point those innovations may be handed off to the industry partner. Industry-based researchers may also enlist the McNair Center for laboratory services in support of their work, including product development and prototyping as well as testing and evaluation.

Workforce development

Students who have earned master's degrees through McNair are already enriching the composites industry in South Carolina and beyond. Graduates have entered the employ of Boeing and other aerospace companies, and have come aboard at US composites companies, such as Carbon Conversions (Lake City, SC) and Crawford Composites (Denver, NC), as well as equipment supplier Ingersoll Machine Tools.

Outside of the master's programs, several efforts at McNair promise to grow the composites workforce well into the future. In the K-12 arena, for example, the center partners with organizations that promote curricula, camps and other activities tied to STEM-centered education programs.

LEARN MORE

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

Read more online about the center's AFP capabilities in "McNair Center installs Ingersoll Lynx AFP machine" | short.compositesworld.com/McNairLynx

To spark interest among undergraduates in composites technology, McNair has been offering courses, such as Basic Mechanics of Materials, to USC juniors and seniors as part of the mechanical engineering aerospace minor. It also awards a McNair Junior Fellowship to USC undergraduate students as early as their freshman year.

McNair Junior Fellows are assigned to work with McNair graduate students and faculty, and enjoy access to McNair's technologies and facilities. "We try to help these students discover what they like," van Tooren says. "They can figure out if they are 'made' for experimental work." After three semesters, Junior Fellows are invited to apply for research assistant positions at the Center.

The Center's professional outreach program, McNair Advance, offers certification in CATIA as well as other training courses to support professionals who work in the more than 500 aerospace companies with facilities in South Carolina. Course subjects include An Introduction to Composites Design and Manufacture, Vacuum Infusion, Introduction to Robotics, and Airframe Structural Design. Through McNair Advance, USC is one of only two US universities recognized as a Dassault Systèmes (Vélizy-Villacoublay, France) Certified Education Partner.

Offering courses for professionals was new ground for those at McNair. It involved both faculty and non-faculty staff, and getting the program up and running at the Center involved some trial and error. "At first, we thought we could just advertise short courses and people would sign up," van Tooren recalls. "They don't! So, it must be very targeted. Now our courses are offered 'on demand.'" Siemens (Munich, Germany) is a large sponsor of McNair, having provided all its software; a recent pilot course was focused on Fibersim. McNair also put on a vacuum infusion course sponsored by DIAB International AB (Laholm, Switzerland), and a course on dry fiber technology.

A growing footprint

Given the above, it's no surprise that the McNair Center is expanding its facility's initial 1,395m² workspace to 2,648m² in 2018. The number of faculty, students and industry partners is expected to mirror this growth. More significantly, the McNair Center intends to continue to grow its impact on composites innovation, application and workforce in the coming decades. CW

ABOUT THE AUTHOR

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General aviation: Reconceiving the personal plane

Enabled by FAA rule changes, small plane manufacturers today are moving beyond the private "pleasure" craft to cutting-edge technologies engineered to offer an affordable means to avoid urban gridlock.

By Michael LeGault / Contributing Writer

» The general aviation (GA) market has historically been more a niche than a mass market. That's especially true of one- to as many as seven-seat GA aircraft used mainly for recreation and operated from short-takeoff-and-landing airfields of a half-mile or less in length. Notably, these smaller craft have been the incubators for a variety of cutting-edge, sophisticated aerodesigns — much more so than larger commercial aircraft. But in the aerospace marketplace, they've been seen and sold largely as pleasure craft, and sales and manufacturer histories have reflected that reality: When the economy and the paychecks of the well-paid are up, sales are good. When the reverse is true, sales and plane makers suffer. That could be changing.

The "personal plane" market has been caught up in a recent trend, instigated, in an unusual twist, by innovators in the ground transport market, and could become a significant, composites-consuming segment in the effort to overcome growing urban gridlock. As several projects profiled here attest, personal-aircraft technology is evolving to meet that challenge. As cities around the world grow more congested and commuters exhaust reserves of patience with car, bus and train transport, the day of the urban air commute grows closer.

The dawn of the air taxi?

Upstart urban ride service provider Uber (San Francisco, CA, US) is taking to the skies with UberAIR. Its fleet of electric-powered vertical-take-off-and-landing (eVTOL) aircraft will ferry commuters between rooftop vertiports, bypassing rush-hour traffic snarls. Aviation OEM partners will build the eVTOLs, using composites, battery-electric propulsion systems and, eventually, pilotless flight control. They'll reportedly carry three to five passengers up to 60 miles, six times faster than street and rail alternatives, at rates comparable to those for high-end ground transport. Source | Uber

Prescriptive to consensus standards

Much of the expansion in this small aircraft sector can be traced to US Federal Aviation Admin. (FAA) regulation changes made more than a decade ago. In 2003, that agency created an entirely new personal aircraft category, Light Sport Aircraft (LSA). The FAA defines an LSA as a two-seat aircraft, other than a helicopter or powered-lift vehicle, with a maximum speed of 120 knots (222 kmh) and a maximum gross takeoff weight of 1,320 lb/598.8 kg (1,430 lb/648.6 kg for seaplanes). The LSA regulation also broke new ground in that it did not set the typical *prescriptive* standards for LSAs — that is, those that describe *how* an aircraft design must accomplish a desired result. Instead, it issued *performance*-based standards, those that describe only the required end-result. Therefore, airframers could henceforth use consensus standards, such as those developed by industry organizations such as ASTM (West Conshohocken, PA, US), and approved by FAA, to design and build such aircraft, so long as the aircraft built to those standards demonstrate performance to FAA-prescribed levels.

Further, the FAA provided for a new Sport Pilot License (SPL). Although it restricts flight time to daylight hours and has a flight ceiling restriction, it requires only *half* the time (20 hours) necessary to acquire a full pilot's license. This opened practical aircraft ownership to a much wider portion of the buying public. Indeed, more than 130 certified aircraft models now meet LSA criterion.

One of the first aircraft designed to LSA requirements was the *ICON A5*, an amphibious sport plane designed with an all-carbon fiber composite airframe, i.e., fuselage, wings and horizontal stabilizer. The two-seat plane is 7m long by 2.47m high with a wingspan of 10.6m. Its 100-hp Rotax 912 engine burns 91 octane auto gasoline or 100 LL aviation fuel; the plane has a maximum cruise speed of 177 kmh and a range of 724 km. It has a short take-off distance, too: 195m on a runway and 256m on water. Additionally, because the plane was designed with an extra safety feature, specifically a "spin-resistant" airframe that required the use of supplemental materials, the *A5* comes with an as-built gross weight of 685 kg, which exceeds the FAA limit for an LSA-type seaplane by 36.3 kg. In 2013, the FAA granted ICON's petition for an exemption to allow an increased takeoff weight for the *A5* up to 762 kg, in acknowledgement of the enhanced safety afforded by the small addition to the aircraft's weight.

ICON Aircraft began manufacturing the plane in 2014 and, thus far, has delivered 26 of the *A5s*. The company says it has deposits for nearly 1,800 orders on the books. The 2018 base pricing for the *A5* is US$269,000. The company manufactures the plane at its 26,000m^2 facility in Vacaville, CA, and operates a second, 27,870m^2 composites manufacturing plant in Baja, CA. It estimates a potential US$10 billion-plus global market for Light Sport Aircraft, such as the *A5*.

In 2017, the FAA modified air certification standards for small aircraft larger than LSA's two- occupant limit, specifically, those covered in 14 *CFR* Part 23. The new rule replaces several categories of planes (commuter, aerobatic, etc.) with four levels of performance and risk, based on the aircraft's seating capacity. Here, too, consensus standards now replace previously prescriptive standards for manufacturers.

Early LSA-category beneficiary

The ICON *A5* amphibious sport plane is certified to the FAA's Light Sport Aircraft (LSA) standard. The *A5* is built with all-carbon fuselage, wings and horizontal stabilizer, and sports an airframe that incorporates a patented spin-resistant design, making it the first production aircraft to meet the FAA *FAR* Part 23 standard for spin resistance. Source | ICON Aircraft

Pipisitrel (Ajdovscina, Slovenia) recently completed certification testing of the *Panthera*, its new and nearly all-carbon fiber composite-airframed craft (its Kevlar-reinforced composite cockpit is the exception). *Panthera* features a novel design that reduces drag by 50% compared to other planes in its class. With an empty gross weight of 692 kg, the four-passenger plane also is much lighter than those planes — 154 kg lighter than the Mooney International Corp. (Kerrville, TX, US) *M20K* and 318 kg lighter than the Cirrus Aircraft (Duluth, MN, US) *SR22*. Technically a general aviation airplane, the *Panthera* requires less than a quarter mile (402m) for a ground-roll takeoff, meaning it can be flown in and out of most local grass landing strips. The plane is equipped with a 210-hp, Lycoming IO-390 engine, generating a maximum cruise speed of about 185 knots. Tine Tomazic, Pipistrel's director »

From better idea to backlog and big factories

ICON Aircraft (Vacaville, CA, US) manufactures its *A5* at its 26,000m^2 facility in California, and operates a 27,870m^2 composites manufacturing plant in Baja, CA. The company had rolled out 26 of the LSAs in late January this year, and has deposits on the books for more than 1,800 orders. Source | ICON Aircraft

SIDE STORY

Better batteries needed for eVTOLs

Although electric-powered aircraft with vertical-take-off-and-landing capability (eVTOLs) offer a promising solution to those attempting to develop alternatives to urban ground transportation gridlock in today's major cities, one significant obstacle to maximizing their usefulness is battery technology. Prospective urban air taxi pioneers, such as ground transport innovator Uber (San Francisco, CA, US), whose Uber Elevate development arm is tasked with putting together a fleet of eVTOLs, says its future urban air mobility business needs eVTOLs with a useful range of 60 miles. The best of current commercial, certified battery technology, however, can only reliably power such craft to within 75% of that target, or about 45 miles.

The key threshold level of performance required to reach the 60-mile range limit is a battery module with 300 Watt-hours per kilogram (Whr/kg) of specific energy. Current advanced battery modules, which comprise lithium-phosphate and nickel-cobalt battery cells, can deliver about 235 Whr/kg. That's a shortfall of about 25%.

At Uber, Mark Moore, Uber's director of engineering, reports the company is partnering with Tier 1 battery suppliers to lay out several different cell technology development pathways of higher and lower risk. The lower risk pathway would be to find a way to get current commercial battery types (Tesla, for example, is using nickel cobalt battery modules in its cars) to perform 25% better. The higher risk pathway entails branching into R&D on new, untested but promising technology — lithium-metal cells. In the laboratory, these cells have been shown to deliver energy on the order of 400-500 Whr/kg. However, the dramatically improved specific energy characteristics of these cells, Moore says, is offset by manufacturing and lifecycle issues, shortcomings that must be addressed over the coming five years if the cells are to be ready in time for the first of UberAir's commercial eVTOLs.

of R&D, says the fuselage and bulkheads comprise a honeycomb construction, while the wings are made with a foam sandwich. The company manufactures the *Panthera* at facilities in Ajdovscina and Gorizia, Italy, which employ a variety of composites manufacturing processes, including vacuum assist, autoclave and out-of-autoclave prepreg technology. It has also developed a proprietary, in-mold painting process comprising polyurethane paint. The company began shipping the *Panthera* to customers this year.

Novel designs and revolutionary aerodynamics

The launches of aircraft such as the ICON *A5* and Pipistrel's *Panthera* suggest that affordable personal aircraft, built in higher volumes in response to new demand, could be the wave of the future. There are, however, several hurdles in the way: lack of infrastructure, scarce investors and seed money, a certain amount of regulatory "gray area" and uncertainty about the long-term demand for such aircraft in a market saturated with recreational choices.

The magnitude of the challenge is conveyed by several ongoing startup efforts to develop and commercialize personalized aircraft in various guises. Synergy Aircraft LLC's (Kalispell, MT, US) *Synergy Prime* concept is a one- to seven-passenger aircraft designed for transport to and from short community airfields. The plane, intended to be available as a kit or fully assembled, is being designed to fly at speeds up to 483 kmh, moving operators and passengers about six times faster than ground transportation alternatives over similar distances. Founder John McGinnis says one of the key features of the aircraft, its Double Boxtail (DBT) wing-tail configuration, works in combination with other aspects of the overall design to reduce drag at high speeds and to improve *span efficiency*. The key to such efficiency is the aspect ratio of wing length or *span* to wing width or *chord* or wing tip to trailing edge. Wings with a long *span* and a short chord have lower induced drag than wings with a short *span* and a long chord.

Since prototype work began, McGinnis and staff have built and tested 16 aircraft iterations. The current and final full-scale prototype, nearing completion, comprises

14 composite parts, for both the kit plane versions and certified production. Although materials and processes are expected to evolve en route to full commercialization, parts have been built primarily via glass layups, typically a tight-weave, 90-oz, 8-harness satin cloth in two to four layers over Corecell SAN cores 12-20 mm thick, supplied by Gurit (Isle of Wight, UK). Wingskins and other high-load areas comprise knitted ±45° Sigmatex (Benicia, CA, US) 12K carbon fiber fabrics. Synergy has used low-viscosity epoxies with a low-toxicity hardener supplied by MAS Epoxies (South St. Paul, MN, US) to infuse the glass and carbon laminates.

McGinnis says now that the primary design work is complete, the company is preparing to pitch investors to fund the commercial startup and initial production tooling. One potential avenue to increase the audience for personal planes is to build and market them as a feasible alternative to cars and commuting. To build a personal plane that would eventually compete with cars and mass transport, he argues, it will be necessary to achieve a far higher rate of production than is currently practiced. "Making a few parts in an autoclave every day does not make economic sense," he says. "We are looking for mutually beneficial collaborations to further develop some promising production technologies we've kept under wraps that are not compatible with what we could do at home in the garage."

Always marketed as an alternative to conventional commuting and personal travel, Terrafugia's (Woburn, MA, US) carbon fiber composite intense "roadable airplane" is also still a work in progress. The company has successfully completed proof-of-concept demonstrations for two prototypes of its flying car, the *Transition*. The first flew in 2009, and the second in 2012. It is now "finalizing production vehicle design and compliance testing," with first vehicle deliveries expected by 2020. The folding-wing, two-seat vehicle runs on premium gas and is designed to drive like a typical car but, with wings unfolded, to fly like an LSA, with a cruise speed of 185 kmh and a range of about 644 km. The brainchild of MIT-trained Carl Dietrich, the plane won an FAA waiver of the 600 kg LSA weight limit, given the merit of the flying car's automotive safety features, including its passenger "safety cage," which make it heavier. Efforts to certify the *Transition* to both automotive (FMVSS) and aircraft (FAA) standards are a factor in reported ballooning costs. According to a report published in *Endgadget*.com, since testing began on the first prototype in 2009, the estimated base price for the vehicle has increased from US$194,000 to US$300,000-US$400,000 for the current version going through final design and testing.

Although Terrafugia was acquired in 2017 by the firm Zhejiang Geely Holding Group (Hangzhou, China), a multinational automotive manufacturer, Geely Group chairman Li Shufu stated the company is "committed to making the flying car dream a reality" and plans to leverage Geely's manufacturing synergies to aid in its development. »

Personal plane ≠ less sophistication

Pipistrel (Ajdovscina, Slovenia) recently began deliveries of its new, all-carbon composite airframed *Panthera*, featuring a novel design that reportedly reduces drag by 50% compared to other planes in its class. The four-passenger craft has an empty gross weight of only 692 kg and requires less than a quarter mile (402m) for a ground-roll takeoff, making it suitable for operation out of many small, local airports. Its cockpit control panel exemplifies the high level of flight-control sophistication that can be found in today's GA aircraft, making the jump to Uber's pilotless air taxis less "science fiction" than it might appear. Source | Pipistrel

Battery-electric capability

Pipistrel's *Alpha Electro*, the company's second battery electric plane, features a 126-kg battery pack that can be removed and replaced in minutes or recharged within an hour, reportedly as simply as a mobile phone. The company uses a variety of composites manufacturing processes, including vacuum-assist, autoclave and out-of-autoclave prepreg technology to manufacture the plane's ultralight airframe (empty weight (251 kg), keeping maximum take-off weight as low as 550 kg. Source | Pipistrel

Elevating the industry

As general aviation technology has evolved and advanced, capitalizing on the weight savings and other benefits of building with composites, the concept of affordable aircraft able to move people short distances, quickly and economically has taken on a life of its own. Charter services and business jets have served those who prefer not to stand in ticket lines and wait for security screens at crowded airports for years. But as long commutes and the resulting traffic snarl have increased, the availability of technology, the will of designers and builders and the pressing needs of urban commuters have converged. The result is a phenomenon encapsulated by a new concept: *on-demand aviation*. In essence, the air taxi.

In the US, Uber (San Francisco, CA) is pitching its plans, announced last year, to launch an urban, airborne ride-sharing business, UberAIR, as a natural extension of its urban ground transportation services. The service will comprise a fleet of three- to five-passenger eVTOLs operated from building-top pads or "vertiports." The company has set an ambitious goal of 50 demonstrator eVTOLs built and delivered for testing by 2020, with fully commercial service startup targeted for 2023 in two US cities, Dallas-Fort Worth, TX, and Los Angeles, CA.

A study conducted by Uber (San Francisco, CA, US) in conjunction with Uber Elevate — a development program announced last year to build an urban air mobility platform called UberAIR, via a fleet of electrically powered, vertical take-off and landing (eVTOL) aircraft — found that using an eVTOL to commute from San Francisco's Marina to San Jose during rush-hour times would take about 15 minutes, shaving nearly *two hours* off the time it would take to travel by car.

Although the first full-scale aircraft for Uber Elevate have yet to be built, Mark Moore, Uber's director of engineering, says

■ **Early air taxi prototype**

Uber eVTOL build partner Aurora Flight Services (Manassas, VA, US) flew this two-seat, one-quarter-scale proof-of-concept model in 2017. The 6.6 ft/2m long vehicle is equipped with eight horizontally oriented propellers for vertical takeoff and landing and one set of vertical propellers in the rear to power fixed-wing flight. The aircraft's electric propulsion system was derived from that used on the company's all-carbon 24A *X-Plane*, now in development for DARPA.

Source | Aurora Flight Services

■ **Composites-enabled aerodynamics**

The unique design of Synergy Aircraft LLC's (Kalispell, MT, US) *Synergy Prime* concept's double boxtail (DBT) located above and behind the wings differs from previous, non-planar DBT designs in that it created a downward, stabilizing force that counters induced drag, resulting in safer low-speed handling.

Source | Synergy Aircraft LLC

lightweight, advanced composites will interface with distributed electrical propulsion and autonomous/pilotless technology as the three core technologies in the design of Uber's eVTOLs, which will fly passengers at speeds up to 322 kmh over a maximum range of 100 km (see the Side Story on p. 28).

Moore reports that Uber invested much time conducting a thorough analysis to ensure the company's UberAIR effort would find a mainstream market. "This is not a moonshot," he emphasizes. "This is all about a pragmatic investment in a product development program, and it is essential that we understand all the various cost elements." Moore says it is Uber's core expertise as a software developer for ride sharing that lends a compelling rationale for the venture — one entailing a costly investment in a radically new, disruptive technology — making the concept feasible, and less risky than it first appears. Each eVTOL aircraft will travel six times faster at peak traffic times than ground vehicle transportation. The service also will capitalize on Uber's pooling technology, so there always will be at least three to four paying passengers per flight, compared to one paying client using one of the company's premium ground services (e.g., UberX, UberBLACK, UberSUV). Given the increased speed of travel and the greater number of paying passengers, the service is expected to be approximately *20 times* more commercially productive than ground-based Uber. Consequently, when the service is out of the development cycle, UberAIR fares are expected to be only slightly higher than those for Uber's higher-end ground transport services.

The company has convened an international array of aerospace OEMs to design and build eTVOLs, including Aurora Flight Services (Manassas, VA, US), Bell Helicopter (Fort Worth, TX, US), light plane manufacturers Pipistrel (Ajdovscina, Slovenia) »

Ready to enter the production mainstream

The aft canopy of Synergy Aircraft's *Synergy Prime* LSA concept is shown here, under vacuum infusion. The part has a complex geometry comprising interlocking rails, fingers and lips. It is one of the plane's 14 major components built from either glass fiber- or carbon fiber-reinforced composites. Synergy is looking for investors to launch commercial production and partners to realize series production methods that will make the plane competitive in the mass transport market. Source | Synergy Aircraft LLC

and Mooney International, and regional commercial and business aircraft builder Embraer (Sao Jose dos Campos, Brazil). Each will independently develop an eVTOL. Other than the three required core technologies and some specified commonality in the interior look and feel of the aircraft cabin, there is no plan to produce vehicles that conform to a common platform. This is by design, Moore says, noting even at this early stage that each partner/manufacturing company is developing its own, unique version of eVTOL aircraft, using independently determined design parameters and styles.

Moore credits FAA's decision to establish consensus standards for its LSA category, in part, for paving the way to the less prescriptive approach now used in the design and manufacture of small general aviation aircraft that are larger than LSAs. "These changes are the most significant in the aerospace industry in the past 50 years," he says. "It is a change the aircraft industry lobbied for and one most believe will enable manufacturers to more quickly adopt new technologies, and reduce certification costs."

"Success for us will be having at least three different manufacturers building eVTOLs," Moore adds. "We embrace diversity, partly because it's the best way to develop this new technology, but also because, right now, we are uncertain which design will prove to be better." Because UberAIR ultimately expects to operate in diverse geographic areas, Moore explains, the best eVTOL to service a particular market might be an eVTOL model with a higher speed, longer range or other performance features that distinguish it from other available models.

Aurora Flight Services was one of the first of the participating aeromanufacturers to build and fly a subscale proof-of-concept eVTOL. The 147-kg, two-seat, quarter-scale aircraft, flown in April 2017, has a length and wingspan of 2m/6.6 ft and is equipped with eight horizontally oriented propellers to take off and land vertically, and a vertical prop in the rear to power it for fast fixed-wing flight once airborne. The concept combines technologies from other Aurora projects that also will be incorporated in the 8m long, full-scale version: Its battery-electric propulsion system will be derived from Aurora's all-carbon composite, 24A *X-Plane* project, under development for DARPA; its autonomous flight guidance system will be adopted from

Aurora's *Centaur*, an optionally piloted aircraft in development for the US Navy.

Assuming the UberAIR network grows and expands globally, Moore estimates that production volumes for the eVTOL aircraft will be on the order of several thousand per year per manufacturer, a capacity, he observes, that hasn't been seen in aerospace since World War II. Even at these volumes, however, he expects the cost per aircraft ultimately will be US$1 million or more. Although the earliest models will be piloted, the intention is that subsequent models will be equipped with — and their ultimate price tag will reflect the cost of — sophisticated pilotless flight-control technology, making the vehicles an unrealistic option for individual ownership. Yet, the venture's unprecedented economies of scale could be a boon for general aviation manufacturing overall.

LEARN MORE

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

Read online about the 2003 genesis of the FAA's Light Sport Aircraft (LSA) category in "Light-sport Plane Category Creates Take-off Point For Composites" | short.compositesworld.com/LSAstart

Read online about early Pipistrel and other LSA-type GA aircraft in "Composites in Light-Sport Aircraft" | short.compositesworld.com/PipLSA

Read online about the earliest days of ION Aircraft in "Plane Enthusiasts Plan LSA-compliant Composite Aircraft" | short.compositesworld.com/IONstartup

Application of VTOL technology, and in particular autonomous, electric-propulsion VTOL or eVTOL in the development of so-called "on-demand aviation" has been ongoing around the world elsewhere for a number of years.

In Europe, Lilium GmbH (Gilching, Germany), a startup venture founded at the Technical University of Munich, completed flight testing of its two-seat prototype eVTOL, the *Lilium Jet*, in April 2017. The venture is developing a full-scale five-seat version that it claims it will be the only electric aircraft capable of both VTOL and jet-powered horizontal flight, with a maximum cruising speed of 200 mph. The company has partnered with the venture capital firm, Atomico (London, UK) and is planning to build a network of landing pads in urban areas in the US and in Europe. The company's mission is "to make air taxis available to everyone and as affordable as driving a car," and has set a timeframe of 2025 for operation of its first fully commercial, five-seat aircraft.

Taking a slightly different tack, PAL-V International (Raamsdonksveer, The Netherlands) is building a flying car that, in flight, is neither airplane nor eVTOL, but a gyroplane. The PAL-V *Liberty* also appears to be the most mature of current flying car concepts, with full certification and commercial production expected in 2019, reports CEO, Robert Dingemanse. The carbon composite airframe is being certified to both European and American air (*CS* 27 and *FAR* 27, respectively) and auto (NHTSA and European Commission) standards. It operates on conventional automobile gasoline or "Mogas" available at most airports, and requires 90-200m for takeoff and even less for landing because the craft can essentially land vertically if necessary. Like other gyroplanes, the *Liberty* can be flown at a very low minimum speed of 50 kmh, up to a maximum of 180 kmh. The gyroplane has a maximum takeoff weight of 910 kg which means, in the US, the aircraft qualifies as a LSA and can be flown with a Sport Pilot License.

Upon certification, the company plans a limited-edition build of 90 vehicles, the PAL-V *Liberty Pioneer Edition*, after which it will begin producing the PAL-V *Liberty Sport* production version. While these PAL-V gyroplanes can be flown for recreation, the company anticipates one of the primary uses will be for commuting to and from work, where the combination car/plane is most eminently useful: fly over the bulk of the traffic congestion, land and travel the short remaining distance to the office on wheels.

In 2016, the Chinese drone company Ehang Intelligent Equipment (Guangzhou) Co. Ltd. (Ghuangzhou, China) successfully flew its multi-rotor, drone-style, single-seat aircraft, the *eHang 184*, and has begun testing for final development and certification in the US. Founded in 2014, the company's history prior to the *184* is small, camera-equipped drones. The move to passenger transport with the *184* is a big step up but should not be underestimated. Reviews since its first demonstration flights are strong. The eVTOL vehicle's payload is rated at 100 kg (net weight, 260 kg). Cruising altitude is 500m, flight time is about 25 minutes at sea level with a 1-hour charge time. Four horizontal rotors, with two propellers each, are supported on arms projecting out from the main frame. Flight speed is 100 kmh. Its 2m long by 1m wide main airframe is built from a carbon fiber-reinforced epoxy composite, with some components of aircraft-grade aluminum alloy.

Back in the US, Terrafugia, best known for its flying car, has made a bid for the eVTOL market. Parent company Geeley is funding the build of an eVTOL, the *TF-X*, and Terrafugia has completed static load testing of a 1/10th scale prototype carbon wing. The wing design was validated by the testing — it was able to withstand more than five times the predicted loads. Design and testing continues on the *TF-X*, which Terrafugia is aiming for commercial readiness by 2023.

Which on-demand technology will be in demand?

Ultimately, money, time and the market will determine which types of eVTOL technology in development prove superior in terms of performance and efficiency, and become viable commuting options for the urban masses. The same holds true for personal aircraft, and in this arena the edge required to reach business-sustaining, commercial-level volumes may be even finer. Yet, with unprecedented benchmark projects, such as those of Uber and Lilium apparently well-funded and solidly in the works, combined with the fresh unleashing of powerful new technologies, bold designs and favorable regulations, it would seem the era of affordable, personalized and "on-demand" flight is off the ground and gaining altitude. CW

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Consolidating thermoplastic composite aerostructures in place, Part 2

Thermoplastic composite structures could eliminate the autoclave and fasteners, but will a one- or two-step process prevail?

By Ginger Gardiner / Senior Editor

» In Part 1 of this two-part story, *CW* reviewed the advent and history of thermoplastic composites (TPC) use in structural aircraft components on commercial aircraft. Particular attention was given to in-situ-consolidated (ISC) thermoplastic composites (TPCs), a single-step process in which heat and pressure are applied as (typically) unidirectional thermoplastic tapes are placed using automated fiber placement (AFP) equipment (see Learn More, p. 39). Structures made in this way are fully consolidated and, thus, can achieve less than 2% void content and sufficient mechanical properties. Therefore, no further heat or pressure is needed.

ISC cylinders and tanks have been produced since the late 1980s, and ISC parts have been used in the oil and gas industry for decades. Further, prototype ISC aircraft structures have been demonstrated in assemblies as large as a helicopter fuselage. Yet none currently fly on commercial aircraft.

As noted in Part 1, ISC fully consolidates the laminate *as it is placed*, achieving target void content and mechanical properties as the TPC cools. But critics contend the placement/consolidation process is too slow, negating the benefits of the single-step process in terms of overall production speed. Proponents of more

One-step vs. two in TPC airframe structures

One-step ISC integrated skin/stringer wing and fuselage structures have been demonstrated by FIDAMC (above) and Automated Dynamics. Dutch and French development programs (e.g., STELIA "Arches TP" fuselage, top of page) claim faster AFP if consolidation and stringer attachment is via secondary operations.

Source | STELIA

Source | FIDAMC

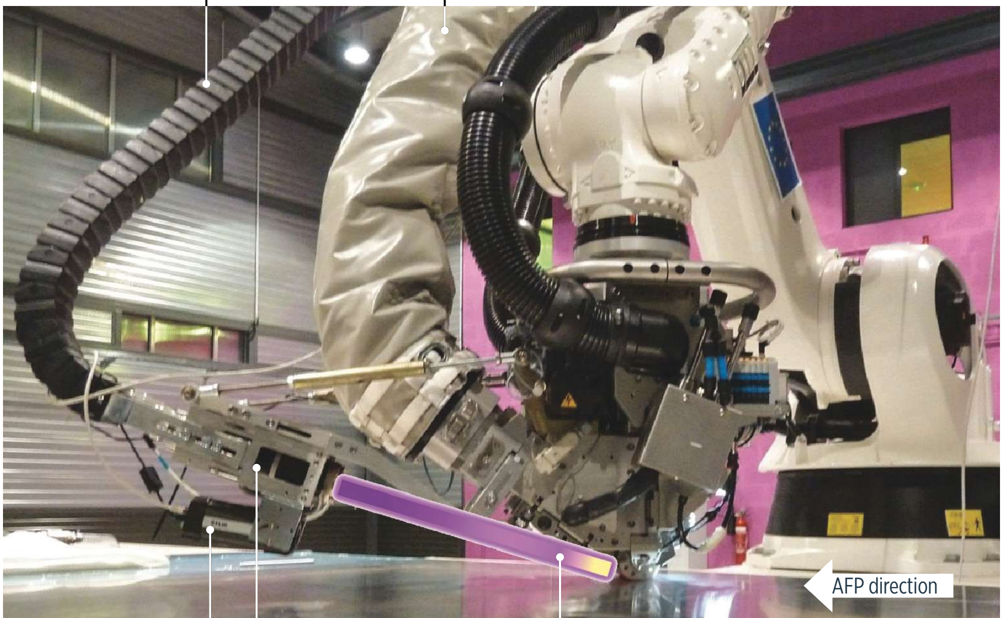


FIG. 1 Controlled laser heating key to in-situ consolidated thermoplastic AFP

As thermoplastic prepreg tape is fed through the AFP head and onto the part, a laser heats it to melt temperature of the matrix, enabling a partial weld (second consolidation step required) or complete weld (in-situ consolidation) to the previously deposited ply. An infrared camera measures the surface temperature of the substrate and incoming tape, providing data used to control laser heating.

Source | Coriolis Composites

conventional, two-step processes insist that they offer the potential for much faster TPC tape placement rates, and result in a faster and less expensive overall part production process, despite the fact that they require a secondary consolidation step, via an oven, autoclave, heated tool or press. In fact, which is faster isn't so clear, and the ultimate parts production speed of each approach can be influenced by multiple factors.

"We could deliver high-performance parts made using in-situ consolidation today," says Cyrille Collart, head of Airbus Innovation & Development, Manufacturing Technologies Composites (Nantes, France). But what will actually fly on future airframes? According to Airbus, it will depend on which technology best meets the targets for each application and aircraft program.

Balancing time and temperature

In its most basic form, an AFP deposition head includes a tape feed and cut mechanism, a compaction roller and a heater (Fig. 1, above). Typically, infrared (IR) heaters are standard for thermoset materials and diode lasers are now the norm for TPCs. As thermoplastic prepreg tape is fed through the AFP head and onto the part, the laser heats it up to and often above the melt temperature of the thermoplastic matrix. This enables either a partial weld to the previously deposited ply, in cases when a second consolidation step will be undertaken, or the complete weld necessary for the single-step ISC application. An IR camera is typically used to measure the surface temperature of the substrate and incoming tape. These data are used in either an open or closed loop system to control the amount of heat supplied by the laser.

"The faster you go, the more power you need, but too much and you will burn the composite," explains Alexandre Hamlyn, chief technology officer and director for AFP equipment supplier Coriolis Composites (Quéven, France). "So, the IR camera senses the layup temperature and alarms the operator if the temperature moves outside of the specified range." He notes that Coriolis machines are used on a range of parts and materials. "The AFP machine is 'trained' during part development and material qualification," says Hamlyn. "This is where the heating profile for each part and material is established." These parameters, saved as recipes, are then selected by the operator. The overall system is controlled by a central computer, providing the advanced degree of control required for primary aircraft structures.

"The longer you heat the tape, the temperature goes through the laminate and builds up stresses in the plies below," says Mike Smoot, VP sales and marketing at Accudyne Systems (Newark, DE, US). "So, it's a balance of temperature and time." He notes this is not as much an issue with thin-walled structures, but more so for thick structures, observing that the latter "will delaminate when machined."

"This is one of the largest issues with ISC," agrees Henri de Vries, senior scientist, composites, in the Structures Technology Dept. at the Netherlands Aerospace Centre (NLR, Amsterdam). "Typically, annealing is required to release the main part of thermal stress, though you can also lower it a bit by keeping the part at 100°C during layup."

The heating element and how it's used also can be a corrective. "We can use different profiles of laser light to heat more length of the tape during placement, which results in longer contact and heating time for better consolidation and less voids," explains Fernando Rodriguez, head of Process Development & Laboratories for FIDAMC (Getafe, Spain). The profile, or shape, of the diode »

Thermoplastic AFP

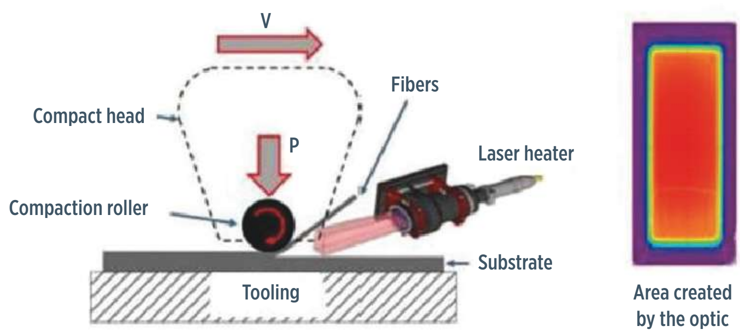
Thermoset AFP

8-tape AFP head

FIG. 2 Thermoplastic AFP laser and optic

Unlike the orange light of infrared heaters used in thermoset AFP, the laser used in thermoplastic AFP gives a purple glow. A laser optic (depicted in the illustration) transforms the laser from a circular to a rectangular cross-section, matching its width to that of the tape/tow being placed at the nip point of the compaction roller.

Source | Coriolis Composites



laser light used in thermoplastic AFP is modified, using an optical fiber and a laser optic (see Figs. 1, p. 35, and 2, above). "This is a very small diameter [1 mm] optical fiber from the diode source to a laser optic, mounted on the head, which transforms the laser source from a circular spot on the laminate to a rectangular output at the nip point, which is matched to the width of the fiber being laid," says Hamlyn. "Our machines can lay widths from 1/8 inch up to 2 inches [3.2 mm to 50.8 mm]. The optical fiber will stretch the laser output to 2 inches [20.8 mm] in width and 1 inch [25.4 mm] in height," he adds.

Speed vs. voids, crystallinity and tape thickness

One key characteristic that impacts process efficiency is void content. "The void content of in-situ consolidated TPC parts depends on the AFP rate, part geometry and prepreg quality," says Robert Langone, president of Automated Dynamics (Niskayuna, NY, US, now part of Trelleborg Group, Trelleborg, Sweden). "Most parts using PEEK have a void content of 4-6%, while most aerospace parts can be as low as 3-4%." Trelleborg produces a variety of ISC glass, carbon and aramid fiber parts, using PEEK for oil and gas parts, and polyphenylene sulfide (PPS), PEKK *and* PEEK for aerospace. "The best we can do is 1% or a little bit lower, but not for every geometry or with every type of thermoplastic tape," he notes.

"For a complex part, we can achieve 96% consolidation (3-4% porosity) and for a flat part, porosity is less than 2%," says Hamlyn. "With flat panels, you can place the fiber more accurately, which helps to increase consolidation. The key point is how we set and control both the process window and the pressure from the high-compaction roller."

Accudyne's Smoot notes that his company struggled with poor tape quality during its ISC development in the 1990s (noted in Part 1; see Learn More). "You couldn't meet porosity or property requirements," he explains. "Accudyne had to consolidate the tape first and then process it with its in-situ laminator machine. In this way, it was able to get within 3% of autoclave properties and even produced some panels that exceeded this."

But Hamlyn notes that thermoplastic tape and tow quality has improved significantly, with porosity as low as 1% possible.

Rodriguez at FIDAMC has seen issues, however, especially in recent stiffened fuselage panel demonstrations. "The consolidation of the laminate between the plies is very good due to the action of the roller," he says, "but there are voids within each ply [intraply] due to porosity in the raw material." He also notes issues with uniformity in tape thickness, width and resin/fiber distribution. The micrographs in Fig. 3 (p. 38) are of CF/PEEK. "You can see the voids and irregular thickness, which then causes issues in achieving compaction," observes Rodriguez. "We need more homogeneous thickness," he adds, "both across the width and length of the tape."

Despite these issues, the degree of consolidation in the single-step process is about 90% of that achieved with an autoclave or hot press. Rodriguez says this is high enough for primary aerostructures, but FIDAMC is working with suppliers — including Barrday (Milbury, MA, US), TenCate (Almelo, The Netherlands), Toho Tenax (Wuppertal, Germany) and Victrex (Cleveleys, Lancashire, UK)— toward the objective of higher quality tapes and a corresponding boost in consolidation, as well as in-situ AFP processing speed.

Another key concern is *crystallinity*, the ordered molecular structure that forms in semi-crystalline polymers, such as PEEK, PEKK and PPS, as they cool from melt temperature to a solid. In general, slower cooling rates increase crystallinity, which results in higher mechanical properties and chemical resistance in the finished laminate. Langone contends that crystallinity matters more for some applications than others. “You’re looking to meet the chemical resistance and mechanical properties of each application, but also stability over the life of the part. The part shrinks as it crystallizes, so you really want that complete during part production in order to prevent changes in part shape while it’s in service.” The goal, he says, is not only to reduce the risk to the part’s dimensional stability but also the risk for residual stress building within the part.

“In my opinion, you don’t need 40% crystallinity,” says de Vries of the typical ideal percentage. “The properties change a little bit, as does the chemical resistance, if you are, say, 5-6% below the maximum [39-40%]. So, 35-36% is good enough, but below this, properties drop off significantly.”

There is also debate about whether PEEK or PEKK provides easier processing with respect to crystallinity. De Vries sees PEKK, which processes at 375°C vs. 385°C for PEEK, as more amenable for AFP, “because the process window is wider.” But not everyone agrees. There are those who contend that PEEK could be used for wing structures, yet PEKK for the fuselage, due to its lower cost. But this also is debated. Most AFP equipment manufacturers and aerostructures development partners are looking at both (see Learn More).

A third factor is tape thickness. At NLR, de Vries sees increased material placement rates possible with thicker materials, which he claims can be processed the same as thinner tapes, with some process window optimization. “We currently use 0.13 mm thickness in standard 0.25-inch wide tapes, which is the certified material from Solvay,” he says. “But we are exploring tapes up to 0.18 mm thick with TenCate in the TAPAS 2 program. We would like to go to 0.25 mm thick in both PEEK and PEKK, but it’s hard to get high-quality.”

One-step process or two?

Although large ISC TPC parts are clearly possible, Arnt Offringa, head of Aerostructures R&T for GKN Aerospace’s (Redditch, UK) Fokker business (Papendrecht and Hoogeveen, The Netherlands), contends, “the challenge for in-situ consolidation is to achieve high lay-down speeds.” ISC has been successful in cylinder, tank and pipe applications in part because the geometry lends itself to one-step processing. “For tubular shapes, high speeds can be attained because tension can be applied to the fibers during the lay-up process,” he explains.

De Vries at NLR adds, “Automated Dynamics achieved this in cylinders early on, because at every 45° and 90° ply, it acts like a hoop, applying hoop stress which prevents deconsolidation and also relieves thermal stress.”

Fokker is the only Tier 1 supplier that has TPC airframe parts flying on production aircraft, but they are made with an »

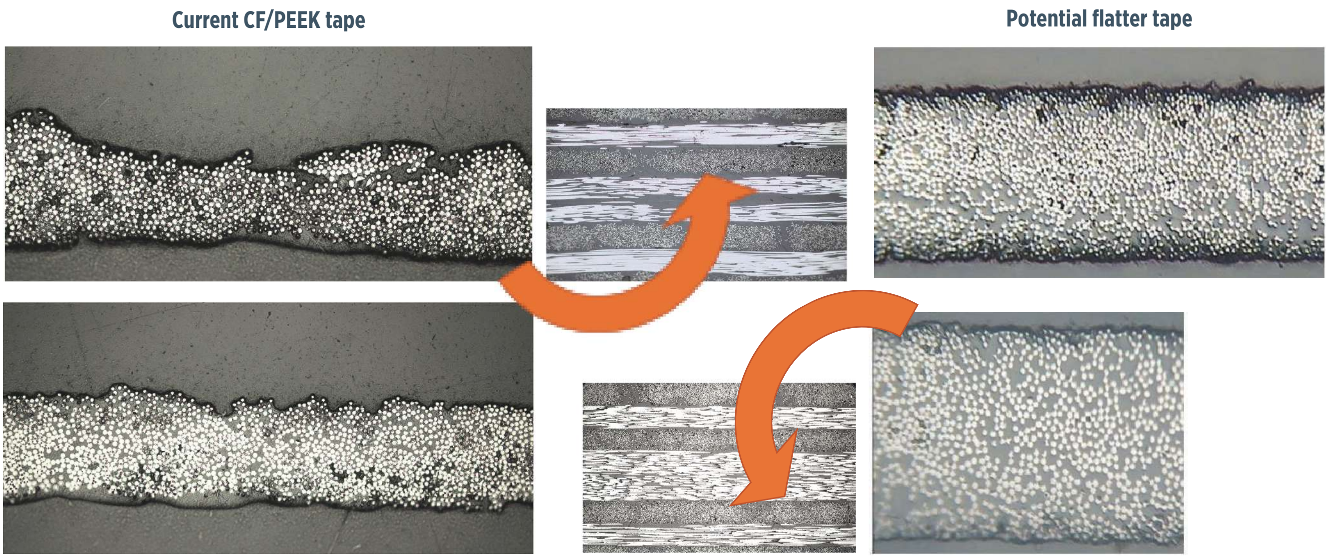


FIG. 3 Flatter tapes with lower void content sought to improve ISC speed

These micrographs from FIDAMC are of a prepreg tape. Voids and irregular thickness make compaction less effective during AFP. Even so, the degree of consolidation for ISC structures can be ≈90% of that achieved with an autoclave or a hot press — high enough for primary aerostructures. But FIDAMC is nevertheless working with suppliers to provide higher-quality, flatter tapes to boost ISC consolidation and speed. Source | FIDAMC

autoclave or press. Offringa, de Vries and most of the Dutch and French partners in the development of TPC primary structures are part of the aerostructures contingent that prefers a two-step process for noncylindrical shaped TPC parts.

Why use an autoclave when one of the oft-cited drivers for developing TPC structures is faster cycle times vs. current thermoset materials? "Because it's still quite difficult to balance speed and quality in AFP," says de Vries. "The faster you go, the worse your quality is, but the cheaper the part." Thus, a second autoclave step allows you to achieve fast AFP speeds and still meet the required void content.

"We are developing a suite of processing technologies, both autoclave and out-of-autoclave," says Offringa. Although the autoclave and hot press apply both heat and pressure, Offringa classes the faster, simpler press option with autoclave alternatives. "Basically, press-forming is an out-of-autoclave process. We are making the next steps in this area toward more complex and larger structures. At the same time, there is a place for autoclave processing, especially for large, strongly curved products with integrated design features. Which process to choose depends on several factors, such as build rate, part size and part complexity."

Hamlyn emphasizes that two-step TPC's second step isn't as onerous, expensive, and time-consuming as its thermoset composites counterpart. Although vacuum bagging is still required, and sufficient time must be allowed under vacuum to reduce porosity to the <2% requirement for primary structures, "the time is not as much as what is spent with thermoset structures," he says. "Today, you spend 4-8 hours heating a huge tool, then 8 hours for polymerization of the thermoset prepreg and then you cool down. With thermoplastics, you are not polymerizing. You heat for 30 minutes to reach 400°C, hold for additional minutes, not hours, and then cool down." He notes there is also investigation into heated tools, which could speed cycle time further.

"We don't do in-situ consolidation," concludes Hamlyn, "but instead achieve the highest consolidation possible without slowing down [vs. thermoset AFP speeds]. We can achieve 1-3% porosity between plies and then do a short vacuum-bagging cycle." He contends that the speed required for ISC, by comparison, will be so slow that parts will cost too much.

De Vries agrees, noting there is still a noticeable gap between ISC AFP rates and processes in which consolidation is completed in a second step. "We can lay at 60-100 mm/sec for in-situ-consolidated thermoplastic composites, but if we lay as fast as possible and then post-autoclave, the speed is 600-700 mm/sec."

In defense of ISC TPC

Automated Dynamics' Langone concedes that two-step consolidation using an autoclave also simplifies certification because it is basically the same process used today for thermoset composite airframes. That said, Langone is firmly in the one-step ISC camp. He says that with laser heating, production speeds for TPC parts can approach those for thermoset parts. "In many cases, you bump up against secondary speed issues like managing crystallinity, inertia of the AFP tool and acceleration and deceleration of the robot system." He notes that actual part production speeds are not simply based on maximum machine speed. "You also have to deal with the complexity of the part, fiber orientations, ply build-ups and drop-offs and stopping and restarting in order to produce near-net shapes and reduce waste," he explains. And these issues slow production regardless of whether the material is thermoset or thermoplastic.

Further, Langone contends that the real advantage is found in the extent of the benefits of eliminating the second step: "A second consolidation step hurts the economics of the parts overall," he says. "We use the standard process of prefabricating stringers, ribs and bulkheads, placing these into a tool/mandrel and then fiber placing on top. The resulting in-situ-consolidated, integrated structure is one of Trelleborg's key capabilities, because you can produce structures without adhesive or fasteners." Although welding also eliminates adhesives and fasteners, it is a third step compared to ISC. These extra steps must be factored into the production cost for a true comparison of one- vs. two-step TPC processes.

> Single-steppers say two-step proponents aren't factoring *all* of the possible steps into their cost calculations.

Rodriguez at FIDAMC concedes that ISC AFP is slower, but believes that a business case can be made in fuselage, if not wing, layup. "Wing structures are very thick," he notes, "so in-situ consolidation is very slow. But fuselage structures are not as thick. With the speeds we can achieve here and without having additional steps, we believe in-situ consolidation can be competitive."

Rodriguez also appeals to the differences in tooling cost: "With in-situ consolidation, the tooling is much less complicated." Like Trelleborg, FIDAMC places fully consolidated stringers and frames into a tool/mandrel and then uses AFP to build the laminate on top, achieving an ISC stiffened skin. "You can control the geometrical shape of all the elements perfectly because you are heating only the last ply of the stringers when you AFP place on top," he claims. "You don't need complicated tooling. For example, in the stringer webs you can maintain the geometrical configuration without mandrels and multi-piece tools." Thus, production is not slowed with installation of tooling inserts during a second consolidation step, and tooling, overall, is less expensive. "It's clear that we need to have a speed with in-situ consolidation that is lower than the two-step process," Rodriguez acknowledges, "but the number of tools and cost/complexity of tools is much better with one-step in-situ consolidation."

Also on the plus side for the one-step camp, *CW* learned just before presstime about a TPC tape alternative that might improve ISC's AFP placement speeds. As leader of the Horizon 2020 project NHYTE, Novotech (Naples, Italy) is working with a variety of partners to build a TPC fuselage panel with an ISC skin and induction welded stringers, both made from a preconsolidated hybrid tape. The tape concept has been patented by Leonardo Aircraft (Rome, Italy). Using an industrialized, continuous process, Novotech sandwiches AS4/APC2 tape from Solvay Composite Materials (Alpharetta, GA, US) between two layers of unreinforced amorphous polyetherimide (PEI). The layers are heated to 400°C and pressed simultaneously with cooling controlled to achieve crystallinity in the PEEK. Initial testing shows good consolidation between the PEEK and PEI. This hybrid tape is then spooled and used in a Coriolis AFP machine to lay an ISC skin. Thus, in addition to integrated skin-stiffener structures, ISC can be used for the skin alone, to which stringers can be welded.

Maturity and work to do for future payoff

Although ISC TPC materials and processing still require significant development work, Hamlyn at Coriolis Composites argues the machine technology is very mature. "The main issue now is how to *use* the machines; that is where there is still much work to do."

"For large parts, we still have to do a lot of work to get the machine time down for ISC," says de Vries at NLR. Alternatively, he sees press forming as very mature. "We've done press forming work for customers all over the world." Welding press-formed stiffeners onto ISC skins may indeed offer a well-balanced compromise and faster route to more TPC primary structures flying on future aircraft.

"For 35 years, Automated Dynamics, now Trelleborg, has made ISC parts every day," says Langone. "From 500,000 parts per year as small as 2 grams, to multiple large parts per year up to 40 ft long and using 2,500 lb of composites." He says AFP will continue to grow in TPCs, driven mainly by the cost savings of shorter cycle times and elimination of the autoclave and mechanical fasteners.

"Today, the key challenge is not about being better than thermoset composites, but in developing a thermoplastic technology which is competitive with metal in terms of performance and cost," says Airbus' Collart. "The mission is to be the lighthouse for composites technologies and components, and thermoplastics are a part of this." CW

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ABOUT THE AUTHOR

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Smarter molding with Smart Cauls

Bridging flaws defeated via male tooling concept.

Source | Spintech

› Composites fabrication has its share of pain points. One is laying carbon/epoxy prepreg into tight mold radii and corners in female molds. It is difficult for manual operators and automated layup equipment to physically access these areas. Further, the tacky prepreg tends to stick to previously placed material on adjacent walls. The result is bridging in the corners because the prepreg is not pressed tightly against the underlying ply in that tight space. Then the corner layup is difficult to compact during autoclave cure, resulting in voids.

Spintech LLC (Xenia, OH, US) has turned this around with its trademarked Smart Tooling Smart Caul, a matched die male tooling product. The Smart Caul enables layup directly onto a rigid male inverse of the female cavity mold, which is then loaded into the female mold. Application of the laminate to the male caul bypasses the physical-access and tack-related issues associated with direct layup in the female mold's tight radii and corners. The technology can be used to create internal mandrels, bladders for hollow parts or any irregular male layup tool shape involving a sharp angle or corner (see endnote).

Here's how it works. A Smart Caul is a male tool made with an epoxy thermoset shape memory polymer (SMP), which behaves like an aerospace-grade rigid epoxy at room temperature, but becomes a flexible but tough elastomer when heated above its activation temperature. Smart Cauls are formed using vacuum-assisted resin transfer molding (VARTM) to pull the SMP resin into a proprietary elastic fabric preform. Then, they are formed to the part shape, using vacuum force applied via vacuum bag in a "form mold" that is constructed to the target part's inner mold line (IML). The Smart Caul is bagged to the form mold, heated to or above 94°C, then vacuum is applied, and the layup is cooled to room temperature. At that point, the Smart Caul has been accurately reformed to the IML part shape (photos at left).

The composite plies are then placed over the now rigid male Smart Caul and placed into the female mold, which is fabricated to the outer mold line (OML) of the part. Liquid or semi-permanent mold releases, such as **Airtech International Inc.'s** (Huntington Beach, CA, US) Tooltec CS5, or a silicone coating may be used here. The part layup over the Smart Caul is bagged to the OML mold, vacuum is pulled and the assembly is autoclave- or oven-cured.

Tom Margraf, Spintech's director of engineering, says, "During cure, the Smart Caul transitions from a rigid to an elastomeric state and evenly translates consolidation pressure across the entire part, consolidating the laminate out against the cure mold."

The company has demonstrated many Smart Caul tools. In its RTM Smart Caul demo, a braided preform was applied to the formed IML Smart Caul, then assembled with an OML RTM mold. An internal vacuum bag was then assembled inside the Smart Caul and sealed to the inner surface of the OML mold. The part was infused using only vacuum at 52°C, says Margraf. When infusion was complete, the mold temperature was increased to transition the Smart Caul from rigid to elastic state, with pressure inside the caul increased to 45 psi (up to 90 psi can be applied) to expel any excess resin and create hydrostatic force to compact voids. Then, oven temperature was increased to 124°C for four hours during cure. The cured part and Smart Caul were demolded, then postcured at 177°C. The Smart Caul was demolded while still elastic. Although quantitative inspection was not conducted on this article, it presented no visible porosity and had a computational fiber volume of 57%, says Margraf.

Margraf stresses that many production scenarios are possible: "With the Smart Caul, you can achieve good IML control, key for some parts. The mandrels can be directly overbraided or filament wound with dry fabrics, then infused. Or, the caul can be used with prepreg and hand layup, or automated tape laying processes."

Smart Caul technology is reportedly more cost-effective and less capital-intensive than metal tooling, eliminates the complexity of multi-piece molds. Layup is faster, because the male bladder shape is easier to access, yet it is clearly able to mimic complex part shapes. Airtech's optional semi-permanent release coating saves the expense and time of repeated mold release applications, and, says Margraf, at about 2.54 mm thick, it is a "very light and maneuverable caul, yet one still rigid enough for layup."

Read more online in the *CW* feature titled, "Smart tooling cuts time and risk for complex unitized composite structures production" | **short.compositesworld.com/SmartTool** CW

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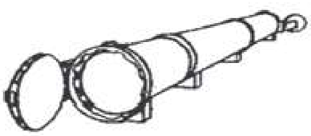

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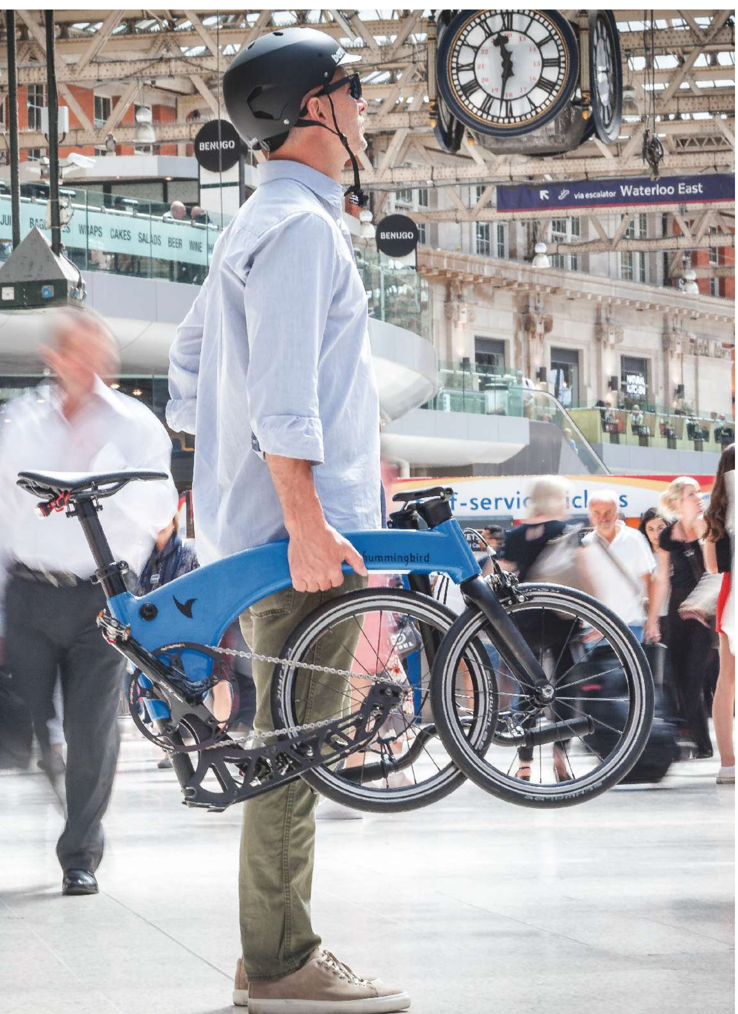
SHOWCASE

Composites-intensive folding bike: Simplifying multi-modal transportation

The world's lightest folding bike relies on CFRP for high stiffness and strength at low weight.

By Peggy Malnati / Contributing Writer

» Folding bicycles hold the promise of an easier life for urban commuters who now switch from bike to train/subway or bus. A bike that can be folded, carried to work, then redeployed upon return to the street eliminates the cost of locker storage in public locations, with the attendant risks of theft or vandalization. Unfortunately, the reality, today, in such multi-modal transportation arrangements is that most folding bikes are fairly heavy, not so compact and uncomfortable to ride any great distance. That is changing, thanks to an innovative UK-based startup.



Engineering challenges

Folding bikes must be strong and stiff enough to take daily pounding on concrete and asphalt, yet light enough to carry. They must fold compactly for carrying/storage, but redeploy quickly and easily. Not surprisingly, they're often made of composites — particularly carbon fiber-reinforced plastics (CFRP), but the challenge has been to reduce mass and folded dimensions, yet build a bike that can hold up to daily use without becoming cost-prohibitive.

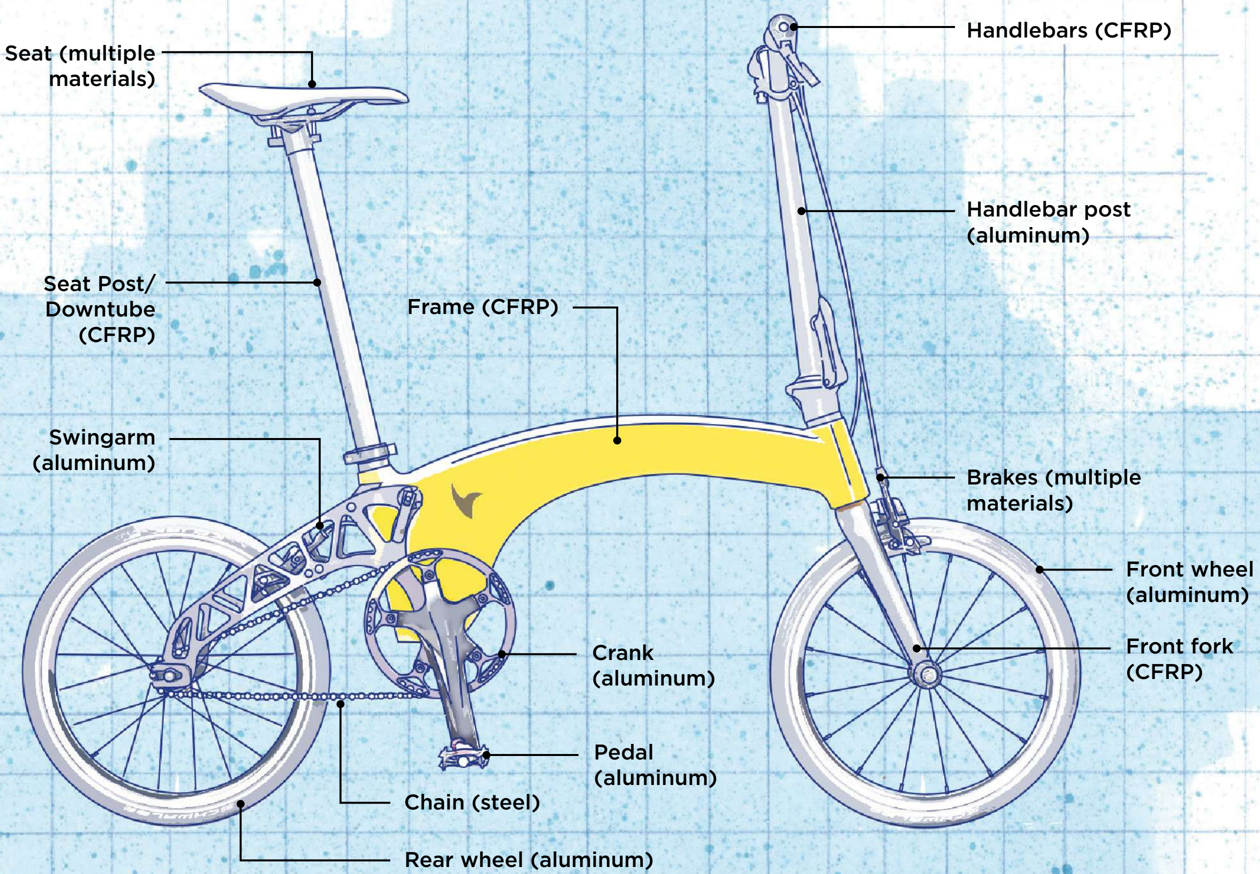
Architectural modelmaker and biking enthusiast Petre Craciun recently accepted the challenge to build a better folding bike after watching girlfriend Ligia Stan, who commutes around London, struggle to carry her heavy bike upstairs to their apartment. The result, created with support from motorsport and advanced-engineering group Prodrive (Banbury, Oxfordshire, UK), is the *Hummingbird*, (now sold by Hummingbird Bike Co. Ltd., London, UK), said to be currently the world's lightest folding bike, at 6.9 kg.

Craciun, self-described as "passionate to optimize things and solve problems," first built a working prototype, then launched a successful fundraising campaign on Kickstarter.com (Brooklyn, NY, US) to commercialize it. Meanwhile, Stan rode the prototype to work and showed her two bosses, who loved how small and light it was. Both became early investors in the new company. One funding partner knew Prodrive founder and chair David Richards, and suggested that he try the bike. Richards gave it a spin and offered to help engineer it for production. The first bike rolled out 12 months later.

A better bike for multi-modal commuters

For urban commuters who must switch from bike to train/subway or bus, most foldable bikes available today are still fairly heavy and not so compact or easy to carry. When the day is done, they're also difficult to redeploy. And they're uncomfortable to ride any great distance. UK-based Hummingbird Bike Co. Ltd.'s innovative alternatives are designed to address those challenges. Made with key structural parts of CFRP, its ultralight bikes collapse and redeploy easily and can even fit into a standard suitcase (see photo, p. 47).

Source (all photos) | Hummingbird Bike Co. Ltd.



DESIGN RESULTS Hummingbird/Prodrive CFRP Folding Bike

- Carbon fiber prepreg with epoxy matrix (unidirectional backing plies with 2x2 twill-weave face plies) provides high stiffness and strength at low weight.
- Low target production volume (200 units/year) for this exclusive bike permits use of CFRP tooling and hand layup/autoclave cure to mold composite components.
- Aluminum inserts that contact CFRP are hard anodized, and all bonded elements are fully encapsulated and sealed with a clearcoat to prevent galvanic corrosion.

Illustration / **Karl Reque**

Design refinement

The bike's basic design has not fundamentally changed since Craciun conceived it. The frame, handlebars, seat downtube and front fork are composite (see photos, p. 46). The swingarm, wheels and drive assembly are aluminum alloy. The engineering focus was to meet safety standards and facilitate manufacture. "The team wanted to create a folding bike that felt a lot more like a traditional bike, but with a taller adjustable handlebar system and seat post to accommodate a wider range of users," notes Craciun. "That gave us the opportunity to make *Hummingbird* fit a wider range of rider positions. We ended up with a saddle that can be moved up/down, forward/back and angled up/down to improve rider comfort and get the best fit."

"The biggest challenge we faced with the base-model bike," recalls Phil Sherwood, Prodrive's composites engineer, "was trying to hit target weight. That made mass a consideration on every single component ... while we also focused on maintaining quality of ride and handling."

"Our original weight target was less than 7 kg, but we aspired to get to 6.5 kg," adds Craciun. "In the end, a few weight trade-offs were made around the drivetrain components in favor of enhanced reliability and availability of components, which left us at 6.9 kg. We wanted people to be able to get their bike serviced at local bike shops, so we steered away from very specialists' stuff."

A unique bike feature is its three-point folding pattern. Its anodized-aluminum Swinglock folding mechanism permits the rear triangle to fold around the bottom bracket without changing chain tension. This eliminates chain tensioners and the need to re-adjust chain tension when the bike is redeployed. A post that doubles as the brake-assembly mount also braces the rear triangle. "The folding mechanism was key to the bike's design and was covered extensively in Petre's sketchbooks on all the different ways to fold »

■ **Carbon fiber composites keep cap on weight**

Currently the world's lightest folding bike at 6.9 kg, the *Hummingbird* achieves this distinction with a carbon fiber composite frame — here, in yellow — and front fork (bottom photo), handlebars (top right) and seat downtube (center left). Retail price is £3,495/US$4,700, including value-added tax (VAT), for a one-speed, or £3,795/US$5,103 for the four-speed version. (Add £500/US$672 to each for the visible-carbon-fiber-weave option.)

a bike," recalls Ryan Vann, a Prodrive structural analysis engineer. "Removing the central frame hinge that's featured on many other 'folders' was key to achieving the ride and handling characteristics we love."

The folding mechanism formed the main design case for integration to the composite frame, and stress analysis and design work focused on making this arrangement work. Given that the main pedaling forces are located around the bottom bracket, this region must be the strongest part of the frame. The team used Abaqus Explicit from Dassault Systèmes (Vélizy-Villacoublay, France) for dynamic structural analyses and Optistruct from Altair Engineering Inc. (Troy, MI, US) for linear static analysis and topology optimization.

"The biggest design iterations involved packaging the rear swingarm assembly to reduce weight, maintain required stiffness and make it beautiful at the same time," explains Vann. "This was quite a change from the original version to its final form where we are doing the same job at half the weight." Although the hardware to achieve this *fold* was predominantly off the shelf, it was necessary to create some bespoke elements. "Some people feel these are design flaws, but it's all very intentional, and in the end, quite a simple system, really," adds Vann.

The folding and locking mechanism design evolved into a system with two levels of folding: *compact* and *more compact*. The first can be executed in three moves, in less than 5 seconds, folding to 110 by 20 by 55 cm. The more compact version (85 by 20 by 55 cm) takes a minute longer. The front wheel is removed and stowed on the swingarm dropout, then the seat tube is removed and slotted between the wheels, making the bike suitcase-friendly (see top photos pp. 46-47).

Materials selection

Although carbon fiber composite was key for achieving structural-performance targets at the lowest weight, the team considered

■ **Small enough to take along and carry on**

There are several *Hummingbird* options available, based on paint color — yellow (shown here), red, burnt orange, black, blue (see opening photo, p. 44) or visible carbon fiber weave — and capability, one or four gear speeds. Deployed bikes (photo, far left) are designed to fit riders from 157-195 cm in height, weighing as much as 110 kg, including baggage. The bike's three-point folding pattern can result in two fold levels: *compact* (hand-carriable, achievable in seconds, shown second from right) and *more compact* (suitcase-stowable, achieved in a little more than a minute, far right).

basalt fiber-reinforced backing plies, because that fiber would deliver a modulus value between those of glass and carbon at lower cost. But basalt use caused weight to exceed the target, so the idea was shelved. "Type and layup of the composite reinforcement were extensively discussed between manufacturing and structural analysis teams to develop a feasible manufacturing solution that still met the design's structural requirements," adds Sherwood.

The components use carbon fiber-reinforced epoxy prepreg (from Microtex Composites Srl., Via Toscana, Italy) that is hand laid up and vacuum-bag/autoclave-cured on CFRP tools. Bladders are used to create hollow tubular structures. For the frame, loose tool inserts are used to create all mating surfaces where seat/head and bottom bracket are inserted and bonded during assembly. Microtex's X1 Matrix epoxy system was selected for its structural performance and visual clarity. Fully cured resin is rated for a continuous-use temperature of 80°C. The 2x2 twill-weave, bi-directional surface plies use 245g fabric while unidirectional backing plies are 660g and also are used as added reinforcements in high-stress areas. Each handmade bike takes about 18.5 hours to produce.

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Working on a bike is a bit of a departure, but Prodrive technicians now apply to the bike the same rigorous process, involving the comprehensive build manuals and end-of-line quality checks they use to assemble complex automotive systems. Manufacturing in Asia would reduce pricing, but the team's concern for quality trumped outsourcing. "This is a beautiful product as well as a functional one and we wanted to retain control of that and be able to stand by the 'Handmade in Britain' tag," explains Chris Walkingshaw, Prodrive project manager.

That tag, however, means the bike's *price* tag (a base of £3,495/US$4,700) will be out of reach for many. "We feel the price represents the quality of the design and the level of craftsmanship that goes into hand-producing every bike," notes Craciun. "We don't plan to make many," he adds — target sales for years one and two are 200 bikes per year, "so it's quite an exclusive club."

That said, *Hummingbirds* have been available to consumers via the company's Web site since July 2017, and from a UK online retailer with several shops since December 2017. They are said to be getting good media reviews and sales are steady. Bikes have shipped to customers not only in the UK but also in Europe, the US, Mexico, Japan and Australia. "Our customers keep sending us pictures of their bikes in all kinds of great locations, so we know they're making their way around the world," laughs Craciun.

Future plans

Looking ahead, Hummingbird and Prodrive are keen to expand into related products. "At the moment, we're focused on, and excited about, the mid-2018 release of belt-drive and electric versions of the bike," says Craciun. "We also have some accessories we'd like to introduce so people can get more from the product they've already purchased." Carrying cases to facilitate transport are on the wish list. "We've tried about 50 aftermarket cases to see if any are compatible, but we have yet to find any we like enough to carry our bike," reports Walkingshaw. A custom case is in the works at Prodrive.

"Even though we are quite a small team …, we've delivered a fantastic product," explains Craciun. "We're aware we can't do everything at once, so we're prioritizing our focus on delivering a great bike. We have future upgrades and models in the pipeline." CW

ABOUT THE AUTHOR

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