



CompositesWorld

# World's Largest Toolmaker: INVAR FOR WINGSKINS

APRIL 2015



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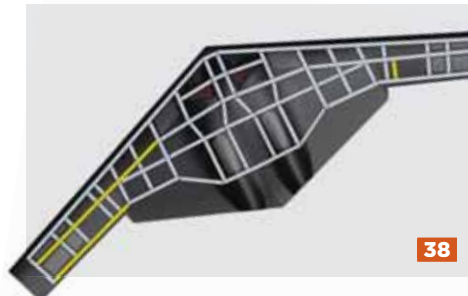
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Ascent Tooling Group, which includes Coast Composites (Irvine, CA, US), Odyssey Industries (Lake Orion, MI, US) and Global Tooling Systems (Macomb Township, MI, US), is the world's largest aerospace toolmaker, and builds more Invar tools, such as this massive aircraft wingskin tool, than any other moldmaker (see p. 34).

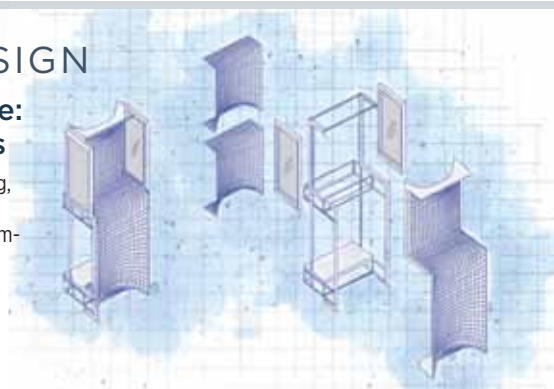
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» The composites industry's largest trade show, JEC Europe, was held March 10-12 in Paris. It was, as usual, big and busy and full of not only innovative technologies but rumors, hearsay and speculation. *CW* was there, as usual, to cover the event. Our initial report

### Notes from JEC Europe 2015: Known knowns, known unknowns and unknown unknowns

is in the News section on the *CW* Web site, and a distillation will appear in the May 2015 issue of *CompositesWorld*. In the meantime, here's my week-old assessment.

#### Known knowns

There was the usual assortment of high-end automobiles on hand to demonstrate exhibitors' composites capabilities. Yet the big question on many lips was: *Will composites take off in automotive? And if so, when?* The consistent answers were: *Yes* and *2020-2025*. The thinking seems to be that automakers and their Tier 1 suppliers are in the midst of sorting out resin, fiber, processing and application options, with an eye toward implementation in the early part of the next decade. This makes sense, given some of the big questions that must be answered by automakers, and none is bigger than that of carbon fiber supply. If an automaker decides to apply carbon fiber to a vehicle on the same scale as BMW has with the *i3*, fiber supply must be guaranteed. Establishing that guarantee is no small task and might require an automaker to establish a partnership of the type BMW created with SGL Group. Meanwhile, many resin and machinery suppliers appear to be developing and proving new fast-curing/short-cycle technologies that they hope will soon find a home in a high-volume automotive manufacturing environment. So, mark your calendar for 2020-2025, but you'd better use a pencil.

#### Known unknowns

There was also a healthy collection of aerospace parts, but after a decade-plus run developing materials and equipment for four very large aerospace programs (Airbus A380, Boeing 787, Airbus A350 XWB, Boeing 777X), many major suppliers to the all-important aerospace industry appear to be asking the same question:

*Now what?* Aircraft programs consumed much attention and resources for a very long time — so long, in fact, that the largesse had become the status quo. However, with the A350 XWB now in service, the supply chains for these programs have been indefinitely fixed. Even the supply chain for the re-winging of the 777X, which will feature carbon fiber composites, is established and locked down. Although there are a few aero programs on the margins that offer nice work packages (i.e., Sikorsky's CH-53K, Bombardier *CSeries*, Irkut's MS-21, etc.), there is no *major* aero program on the horizon. Beyond the horizon, lurking, are the redesigns of the Airbus A320 and Boeing 737, but the year most frequently associated with those programs is 2030. And where and how composites might be used on these single-aisle aircraft is still an open question.

#### Unknown unknowns

One under-appreciated feature of the composites industry is its highly dynamic nature. As someone who came from outside the industry, I understand well that the mix of resin, fiber, tooling and manufacturing processes employed by composites fabricators almost guarantees rapid innovation and fast change. This means that there are composites applications still in their infancy, or yet to come to life, that could one day become dominant — or more dominant. Offshore wind blades, pressure vessels, and oil and gas structures spring to mind.

If JEC is a snapshot of the health of the composites industry, it must be pronounced robust and growing, still in the throes of adolescence but with a promising future ahead.

JEFF SLOAN — Editor-In-Chief



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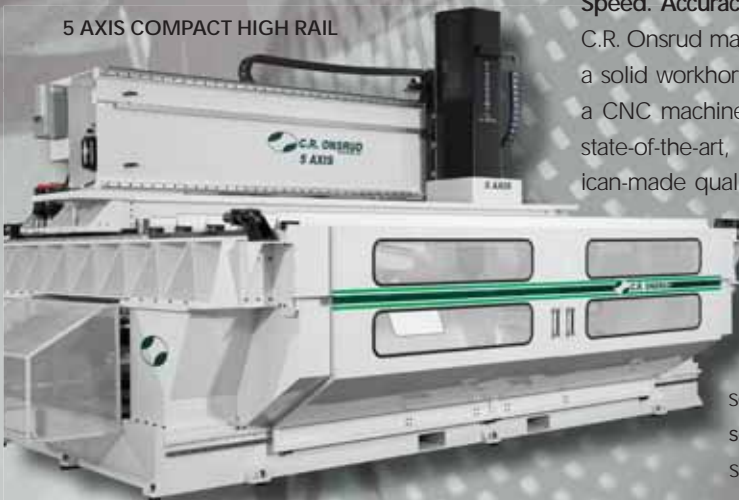
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# Automated composites manufacturing, past, present and future

» The 1970s and 1980s were dynamic periods in the development of automated composites manufacturing. In that time, Brandt Goldsworthy of Goldsworthy Engineering (Torrance, CA, US) and his team pioneered the first commercial pultrusion machines, and developed tape laying and fiber placement machines, numerous innovative custom machines and many variations of filament winding. I was fortunate to spend my early career working for and being mentored by Goldsworthy before becoming his company

manager. It is interesting to look back and consider what has become of those pioneering efforts. Which pioneering processes have survived and become common

Today's product requirements are more challenging than ever, and creative new ... approaches are required.

today? Which processes still have unrealized potential? What are the future advancements in automated processing going to be?

Pultrusion has been one of the fastest growing commercial processes for some time. Pultruded products have clearly established their niche. Today's machines have changed very little in concept from Goldsworthy's original Glastruder. In-die injection is probably the most significant advancement since the process was commercialized. The addition of multiaxial fabrics has enabled pultrusion of more sophisticated laminates. Further development of lightweight and high-strength, yet cost-effective, profiles is the future challenge if pultrusion is to compete head-to-head with traditional materials. Joining pultruded profiles into large, integrated structures is another challenge that must be tackled.

Looking back, it is surprising that Pulforming, a Goldsworthy variation of the pultrusion process, has not been further developed or more broadly applied. Pulforming, which combines step compression molding with pultrusion material infeed technology, can enable continuous, automated manufacture of curved parts and parts with nonuniform cross sections. Maybe this recollection will inspire others to revisit the process and take it to the next level.

Goldsworthy made the first tape layer in the early 1970s and the first fiber placement machine in the mid-1980s, but both were hampered by machine-control technology limitations. The emergence of modern computer control/servomotor technology enabled these machines to become common, productive systems in aerospace. It is refreshing to note that probably the largest use of fiber placement is *outside* of the aerospace market. In the 1990s, North Sails (Milford, CT, US) applied the basic principles of large gantry-based fiber placement to sail manufacturing in a very big way. Literally thousands of fiber-reinforced sails have been made over configurable molds by the company's unique 3DL process.

North's latest development, the 3Di process, is a true composite-laminate sail made using CAD and CAM. Goldsworthy would have been very pleased to see these developments! Maybe the same principles can be applied to large flexible architectural enclosures.

Southern Spars (Auckland, New Zealand) has applied tape laying to carbon fiber sailboat mast manufacture, and some of its projects are very large. Carbon fiber masts more than 46m tall are commonly made, and a recent project produced a 90m mast for a 90m yacht. These masts are stabilized with carbon fiber rigging made from bundled pultruded carbon rods or continuously wound rigging members. In the case of a 90m mast, the standing rigging elements are up to 90 mm in diameter with tensile strengths of more than 900,000 kg. These are serious engineering challenges, met using automated manufacturing technology.

Another Goldsworthy development with still unrealized potential is the combination of filament winding and pultrusion into one machine. Over-winding wheels upstream from a standard pultrusion machine enables manufacturers to make tubular products with optimized fiber orientations, and to do so on a continuous basis. With today's materials and computer control systems, these technologies offer the opportunity to make high-performance tubulars for the oil and gas market in a cost-effective manner.

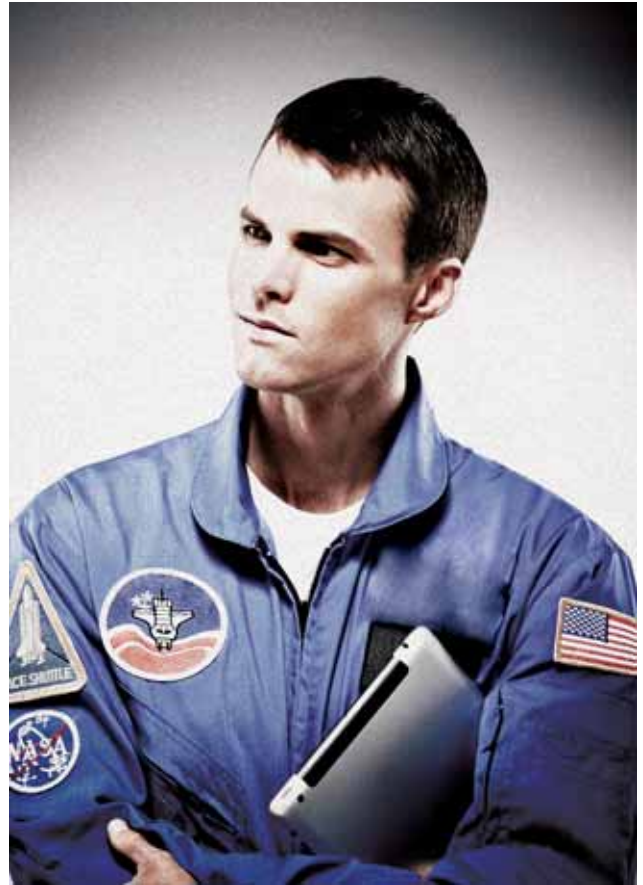
As product designers and manufacturing engineers work to develop future products, it is important to pick the right process or combination of processes. Today's product requirements are more challenging than ever, and creative new processes and approaches are often required. At my current company, VectorSum Inc. (Irvine, CA, US), we strive to find the optimal solution from the rational combination of all constraints, requirements, expectations, capabilities and experience that constitute the boundary conditions of a problem. By imagining each of these determinants as a vector, the sum of the vectors defines the solution. This approach can lead one to step out of conventional practice and come up with creative system-engineering solutions. Much like Brandt Goldsworthy did in his lifetime of contribution to the composites industry. **cw**



## ABOUT THE AUTHOR

Rob Sjostedt is a partner and CEO at engineering and manufacturing consulting services provider VectorSum Inc. (Irvine, CA, US). He has had a 37-year career in composites product development, manufacturing and business management. Sjostedt spent his early career working at

Goldsworthy Engineering (Torrance, CA, US), eventually running the company under the banner Alcoa Goldsworthy Engineering. Subsequently, he established Stoughton Composites (Stoughton, WI, US) to make composite intermodal containers and trailers, was COO in charge of composites development for Beal Aerospace (Dallas, TX, US), developed carbon sailboat rigging for Air Logistics (Azusa, CA, US) and Southern Spars (Auckland, New Zealand), and was CEO of Bal Seal Engineering (Foothills Ranch, CA, US).



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# Aerospace still matters

The automotive industry can thank the aerospace industry for leading the way.

»In November, I bemoaned the fact that the carbon fibers used today for aerospace applications are the same types used 20 years ago, and that little innovation in reinforcements for this market has occurred in two decades. Although much of that is attributable to the expense and time necessary to qualify a new material, *other* aspects of advanced composites in aerospace continue to move forward, but much of the progress has taken place away from the spotlight. If one reviewed composites industry press coverage over

the past couple of years, it would be easy to conclude that the future of advanced composites is in *industrial* applications, most notably as a

significant enabler of lightweight automobile structures, consumer electronics and wind turbines. Aerospace composites are getting a progressively smaller share of “air time,” so to speak.

A year ago, I cited Chrysler’s (FCA US LLC, Auburn Hills, MI, US) Francois Castaing, who notably said in 1985: “Steel is for cars, aluminum is for airplanes, and plastics are for toys.” Today, “plastic” composites are well established in airplanes, and aluminum is growing exponentially in cars, with advanced composites knocking on the door to supplant aluminum there as well. And steel? It’s unclear what markets offer upside for this legendary material, as even bridges and buildings are seeing increasing substitution by composite materials. That’s a story for another day.

It’s easy to take aerospace composites for granted: There’s not much metal left to replace in certain applications: Satellites, UAVs and helicopters are composites-intensive already, and I’m not convinced military aircraft will creep much beyond the 35-45% content level. Titanium is too critical to those designs, and that market doesn’t move fast where change is concerned. Production *volumes* can increase — UAVs, in particular, will add some tonnage, but the UAV segment won’t have as big an impact on aerospace composites as commercial aircraft. And the recent history of that segment, notably the Airbus A380, the Boeing 787 and the Airbus A350 XWB, suggests that composites have conquered this arena as well. That said, the battle for material supremacy in this segment is far from over. Although the most recently certified aircraft have high levels of advanced composites content, the redesigned Boeing 777, the 777X, will have carbon fiber wings but *retain* an aluminum fuselage. Single-aisle upgrades, including the Airbus A320neo and Boeing 737 MAX, are still aluminum-intensive, extending their lives without significant use of advanced composites in primary structure. Full redesigns have been pushed back. Metals suppliers are fighting back against composites, with new alloys, including aluminum-lithium. It is unclear what materials will prevail in this major aerospace sector.

There is one undeniable fact: Decades of investment in aerospace applications of advanced composites have enabled the current revolution in industrial composites, and will continue to do so. Carbon fiber is an obvious example — the aerospace industry has driven the development of most grades of this versatile reinforcement, and aerospace demand (largely defense-based) has fostered initial capacity and consistent quality. Early adopters in the sporting goods and industrial markets were able to tap into those benefits. Similarly, high-strength fibers, with 700 ksi (4,800 Mpa) tensile strength, are the material of choice for Type IV compressed natural gas and hydrogen storage cylinders. Downstream products, such as prepregs and carbon fabrics, developed initially for aerospace, are now used in multiple industrial markets, processed by autoclave and out-of-autoclave methods. Starting with Formula 1 racers, then migrating to supercars and sports cars, carbon composites have most recently found their way into commuter vehicles, such as the BMW i3. The automotive industry can thank aerospace for leading the way.

Core cross-cutting technologies, including nondestructive methods for detecting porosity in molded parts, and joining of composites to metal, have been led by the aerospace market. Applications of key design and simulation tools to composites, including CATIA, ABAQUS and Fibersim, owe their development and reputation to their pioneering use in aerospace, where they continue to be refined. These technologies will play a big role in driving down development cycle times and confirming quality of automotive structures, wind turbine blades and much more. For composites to make further inroads into commercial aircraft, the industry must drive costs out and part production capacity up. Increased emphasis on out-of-autoclave approaches is one strategy in the battle against metals. Others strategies — structural optimization (moving away from “black metal” designs), parts consolidation, and joining components with adhesives instead of fasteners (see “Building TRUST in bonded primary structures,” p. 38) — will yield a more competitive landscape. And, like the innovations that came before, the industrial composites market will leverage this new aerospace technology, to yield the same. **cw**



## ABOUT THE AUTHOR

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

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# Methods for interlaminar tensile testing of composites: A comparative evaluation

» As the name suggests, interlaminar tensile testing is performed to measure tensile properties in the through-thickness direction of composite laminates rather than the more commonly measured in-plane properties. Although the out-of-plane tensile modulus,  $E_3$ , and Poisson's ratios,  $\nu_{31}$  and  $\nu_{32}$ , can be obtained, the *interlaminar* tensile strength is of greatest interest. It's common to assume that  $E_3$  is equal to the in-plane transverse tensile modulus,  $E_2$ , making its measurement of lesser importance. This is not the case, however, for the interlaminar tensile *strength*. Differences in manufacturing methods can affect the bond strength between the plies of a composite laminate and produce significant differences between the interlaminar tensile strength and the *in-plane* tensile strength transverse to the fiber direction. Therefore, this column will focus on test methods available for measuring this interlaminar tensile strength property in composites.

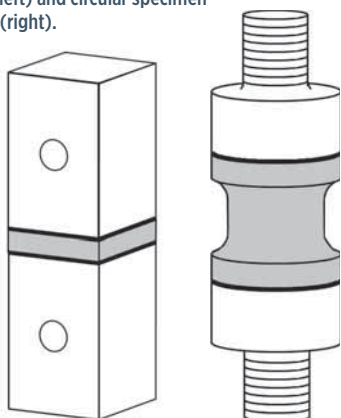
Fiber-reinforced composite structures are designed with fibers positioned to carry tensile loads in desired in-plane orientations, so why is interlaminar tensile strength of such interest? One reason is because the interlaminar tensile strength can be *two orders of magnitude less* than the in-plane tensile strength in the fiber direction. As a result, relatively small interlaminar tensile stresses can lead to disbond failure between composite plies. This strength property also is used in progressive damage modeling of composites for predicting the formation of delaminations in composite structures. Finally, as mentioned above, the interlaminar tensile strength is used to assess whether an as-manufactured composite has acceptable bond strength between the plies.

There are two general methods in use for interlaminar tensile testing of composites, the *direct* and *indirect* loading methods. The former produces interlaminar tensile stress by directly applying an out-of-plane tensile load to a flat composite specimen. In practice,

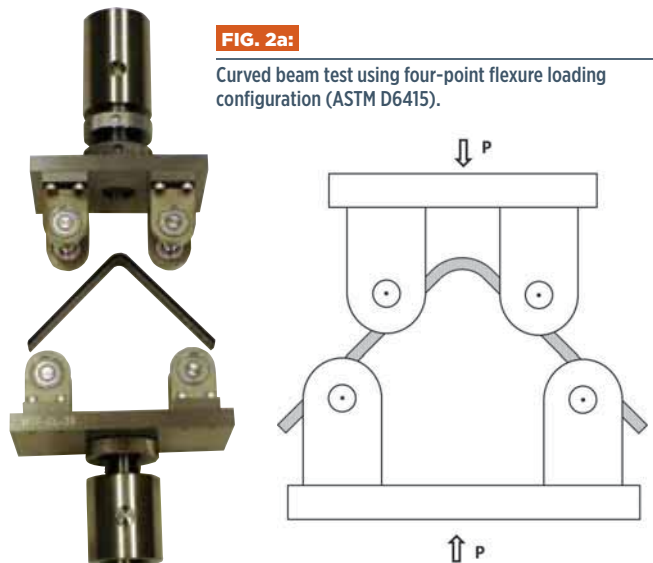
metal fixture blocks typically are bonded to the top and bottom surfaces of the composite specimen and used for load application (Fig. 1). This method, the flatwise tensile test, is described in two ASTM standards that differ significantly. ASTM C297<sup>1</sup> features square specimens and is intended primarily for sandwich composites. ASTM D7291<sup>2</sup> is a more recent standard that specifies circular specimens and focuses on maintaining alignment while bonding the fixture blocks to the specimen. Because the state of stress is not affected significantly by the cross-sectional shape of the specimen, the choice between square and circular specimens often is based on machining and fixturing preferences. In contrast, indirect loading methods generate interlaminar tensile stresses by applying bending moments to curved beam specimens. The most common is the »

**FIG. 1:** Flatwise tensile test configurations: Square specimen per ASTM C297 (left) and circular specimen per ASTM D7291 (right).

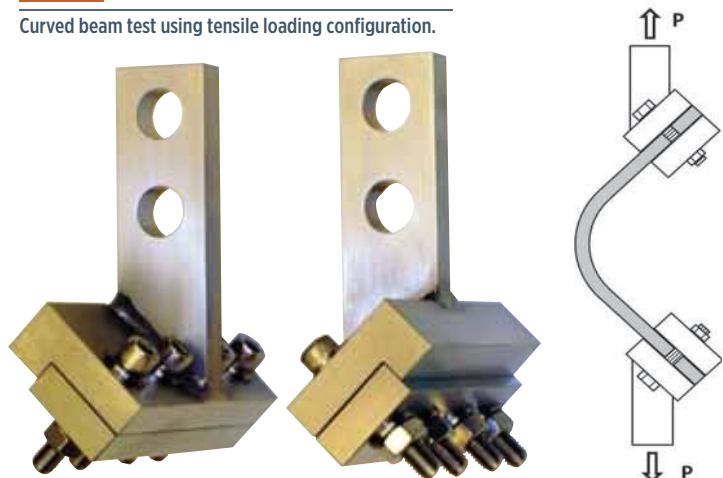
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**FIG. 2a:** Curved beam test using four-point flexure loading configuration (ASTM D6415).



**FIG. 2b:** Curved beam test using tensile loading configuration.





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## Inspection for Automated Composite Manufacturing

### EVENT DESCRIPTION:

Manual inspection of automated composite manufacturing can account for up to 50% of the overall lamination time. Diligent planning with the use of inspection aids provides the opportunity to improve the efficiency of required inspection. Going forward, automated ply inspection has the potential to eliminate the need for manual inspection of the laminate. This webinar will provide real world examples of automated laminate inspection planning, available manual inspection aids for automated composite manufacturing machines and introduce potential automated ply inspection techniques to eliminate the need for manual inspection.

### PARTICIPANTS WILL LEARN:

- Inspection Planning for Automated Composites manufacturing
- Potential Automated Inspection techniques
- Techniques to aid in manual ply inspection

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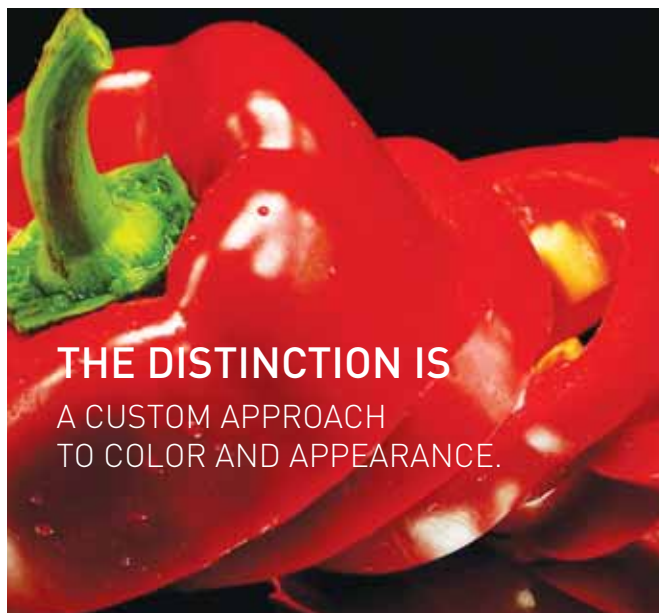
four-point bend loading configuration specified in ASTM D6415<sup>3</sup> (Fig. 2a, p. 10). However, the required bending moment also can be produced by clamping the specimen legs in special fixtures and loading in tension (Fig. 2b, p. 10). In both cases, interlaminar tensile stresses are produced only in the specimen's central curved portion.

So which interlaminar tension test is best? Unfortunately, there's no simple answer, because both methods have shortcomings. One can select the method *best suited* for a particular situation only with a good understanding of their relative advantages and disadvantages. One important consideration is the restrictions that each method places on the test panel used. This may appear to favor the direct-loaded, flatwise tensile test, because specimens may be obtained from a flat composite laminate. However, a bobbin-shaped specimen (Fig. 1, p. 10, right) is often needed to produce acceptable failures away from the bonded fixture blocks. As a result, a relatively thick test panel (25 mm or more) is suggested to produce these tapered cross section specimens.

For the indirect-loaded specimens, the central curved region where interlaminar tensile stresses are produced is often the site of manufacturing problems, such as layer waviness, resin-rich regions and voids. As such, it is questionable whether this test region is representative of a flat laminate. Another restriction that is sometimes overlooked: The curved beam specimen should be fabricated as a unidirectional laminate, with the fibers oriented

along the curved beam's length. The reason? The equation used to calculate interlaminar tensile strength comes from an anisotropic elasticity solution that is valid only for a *unidirectional* composite laminate. For multidirectional laminates, the less meaningful *curved beam strength* (maximum bending moment per unit width) is obtained. A detailed numerical analysis of the multidirectional test specimen is needed to determine the interlaminar shear strength from these specimens. These restrictions associated with the curved beam specimen make the thick flat panel for flatwise tensile testing more desirable.

Before choosing the direct-loaded flatwise tensile test method, however, another important consideration is the procedures required for preparing and testing the specimens from the test panel. For curved beam testing, specimens may be sliced from the curved panel using relatively simple machining procedures. Performing the curved beam test under four-point flexure loading is relatively straightforward as well. For flatwise tensile testing, however, considerably more effort is required in preparing the specimens. After machining specimens from the test panel, their top and bottom surfaces are prepared for adhesive bonding to the metal fixture blocks. Maintaining alignment is critical when bonding the specimens to the loading blocks and during testing. ASTM D 7291 describes an elaborate bonding jig that may be used to align circular specimens during bonding; however, simpler methods are possible as well. Lack of alignment



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produces bending in addition to tensile loading, resulting in a nonuniform stress state and reductions in the measured interlaminar tensile strength. After bonding, the cross section of the circular specimens is machined to produce the desired bobbin shape. Note that these operations require more time and cost than the curved-beam test.

A final consideration concerns the values of interlaminar tensile strength: Should the user expect the two methods to yield comparable results? Not necessarily, because there are some important differences in the specimen stress states as well as the volume of material being tested. With proper alignment, the direct-loaded, flatwise tensile test produces a relatively uniform state of interlaminar tensile stress in the reduced-area test section of the specimen. This favorable stress state is present over a sufficiently large volume of material. In contrast, the indirect-loaded curved beam specimen that's subjected to four-point flexure loading experiences a combined stress state in the curved central region that includes undesirable in-plane tension and compression stresses due to the applied bending moment. These in-plane stresses can be an order of magnitude larger than the intended interlaminar tensile stresses. Additionally, the volume of material in the region of high interlaminar tensile stress is smaller than in the flatwise tensile test.

In general, both methods are known for producing large amounts of scatter in the test results. In the flatwise tensile test, scatter is often attributed to improper alignment, which causes bending stresses in the specimen. For the curved beam test, scatter is typically attributed to manufacturing problems in the central curved portion of the specimen.

There are difficulties and limitations associated with the direct and indirect test methods for interlaminar tensile strength measurement. Both are standardized and in common use, but neither is viewed as completely satisfactory. By understanding their relative advantages and disadvantages, however, users can choose the method that best fits their application. **CW**

#### References

<sup>1</sup> ASTM C 297-04, "Flatwise Tensile Strength of Sandwich Constructions," ASTM International (W. Conshohocken, Pa.) first issued in 1952.

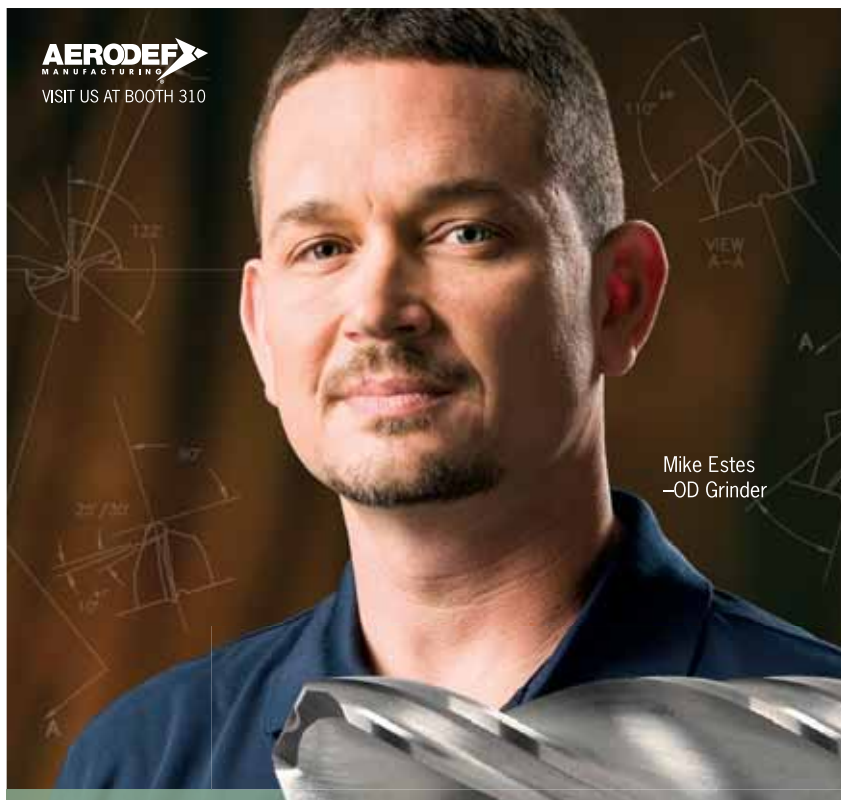
<sup>2</sup> ASTM D 7291-07, "Through-Thickness 'Flatwise' Tensile Strength and Elastic Modulus of a Fiber-Reinforced Polymer Matrix Composite Material," ASTM International (W. Conshohocken, Pa.), first issued in 2007.

<sup>3</sup> ASTM D 6415-06, "Test Method for Measuring the Curved Beam Strength of a Fiber-Reinforced Polymer-Matrix Composite," ASTM International (W. Conshohocken, Pa.), first issued in 1999.



#### ABOUT THE AUTHOR

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



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# CW Business Index at 50.5 – Growth slows for second month

» With a reading of 50.5 in February 2015, the *CompositesWorld* Business Index showed that the composites industry in the United States had expanded for the fourth straight month. However, the index had moved lower in both January and February. Compared with one year earlier, the Index had contracted more than 4% in each of those months. While the annual rate of change was still growing, by the end of February, it had been growing at a slower rate for six full months.

New orders grew for the 15<sup>th</sup> consecutive month. Although the new order subindex fell somewhat from its January number, the trend for new orders has been up, generally, since September 2014. Production was only slightly less active, showing growth for a 14<sup>th</sup> straight month. However, other than in December 2014 and January 2015, production has expanded at a consistent rate since August 2014. Backlogs contracted for a second month in a row. The

backlog subindex, in fact, was at its lowest level since August 2013 and was 17.3% lower than it was one year previously. Further, it was the fourth time in five months that the month-over-month rate of change had contracted, a clear indication that capacity utilization had probably seen its peak rate of growth in the composites industry. Employment continued a growth stint that began in March 2013. Exports continued to contract due to the strengthening dollar. Supplier deliveries lengthened at virtually the same rate in February as in January, which was the fastest rate since April 2012.

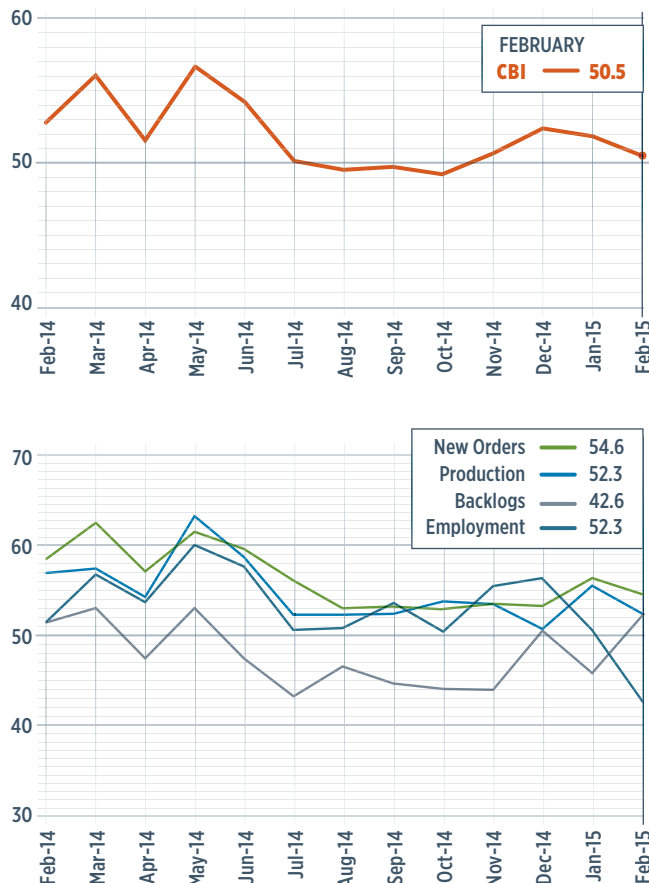
Material prices continued to increase, but at a slower rate. In February, this subindex had declined every month since May 2014. The prices received subindex, meanwhile, had increased significantly since October 2014. In fact, the prices received subindex was higher than the material prices subindex in February for the first time in the CWBI survey's history (since December 2011). Future business expectations shot up in February to their highest level since January 2012.

Slowing growth at larger composites fabricators was the reason the overall Index slowed in February. At facilities with more than 100 employees, the February subindex fell to 50.1 from 65.3. And, at plants with 50-99 employees, the subindex fell to 48.1 from 56.0. Both of these plant sizes had been growing at much stronger rates during the second half of 2014. Facilities with 20-49 employees contracted for the sixth consecutive month. Facilities with fewer than 20 employees, however, expanded for the first time since June 2014. In fact, these were the fastest growing facilities in February.

Regionally, The North Central – West was the fastest growing in the US for a third straight month. The only other region to grow in February was the West. The Northeast contracted at a moderate rate and was followed by the North Central – East and Southeast regions.

Future capital spending plans exceeded US\$1 million for the third time in four months. And, for the second time in four months, the month-over-month rate of change increased by more than 20%. However, the annual rate of change contracted in December 2014 and in January and February of this year. **CW**

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



## ABOUT THE AUTHOR

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

Vanderbilt University and an MBA from the University of Cincinnati.  
skline2@gardnerweb.com

## Composite wind turbines on the Eiffel Tower, carbon fiber exoskeletons on a car assembly line, and reports from Australia, Brazil and the UK.



### ENERGY

#### Eiffel Tower harvests wind energy for tenants with vertical-axis turbines

As the CW staff prepared to jet off to Paris to attend annual composites trade events staged there each year in early March, we got wind of the fact that the Eiffel Tower had been outfitted to use its lofty position to harvest energy from the wind. The tower's iron-clad framework gives this masterwork of engineering a certain antiquity and, as a result, an unalterable timelessness. But over time, it has been altered in big ways and small. The two vertical-axis wind turbines (VAWTs) mounted along its lower deck, in fact, rate in the "small" category. Although the turbines are clearly visible from Trocadéro Square, which offers a direct view of the tower from the opposite side of the Seine, they're barely visible from the foot of the tower lost in the latticework maze of iron that holds everything together.

Perched about 122m above the ground, atop a second-level restaurant, the VisionAIR<sup>5</sup> composite turbines with distinctive helix-shaped blades, supplied by Urban Green Energy (UGE, New York, NY, US), will provide 10,000 kWh of electricity per year to commercial businesses on the first level of the tower.

The curved, tri-blade VAWTs were designed and installed by UGE. The glass fiber-reinforced blades were painted in a brown-grey hue to match the structure, and extra vibration dampers were added to make sure the turbines wouldn't disturb diners at the *Jules Verne* restaurant below. When



Source | Urban Green Energy

running at full speed, the turbines only produce about 40 dB of sound.

Each blade had to be hoisted by hand and pulley up to the second floor, and secured within the building's tight lattice structure along its southwest corner. The entire installation had to be done at night, as well, because the Eiffel Tower is open to the public until 11 p.m., seven days a week.



### AUTOMOTIVE

#### Carbon fiber exoskeleton supports Audi assembly line employees



Source | Audi

Carmaker Audi AG (Ingolstadt, Germany) is calling it the "Chairless Chair," but it really is a carbon fiber composite exoskeleton, currently undergoing trials at the company's plant in Neckarsulm, Germany. Strapped to the back of each leg, the device allows employees to "sit" (relax leg muscles) without actually sitting in a chair (see photo). For some

assembly operations, the exoskeleton enables the employee to sit in an ergonomically favorable position instead of standing. Chairs and stools currently used in some assembly operations as temporary aids become unnecessary. Audi hopes the exoskeleton will improve worker posture and reduce absenteeism due to leg strain.

The exoskeleton was developed by Audi with start-up firm noonee AG (Rüti, Switzerland). Fastened with belts to the hips, knees and ankles, its two leather-covered surfaces support the buttocks and thighs while two carbon composite struts adapt to the contours of the leg. Struts are jointed behind the knee and can be hydraulically adjusted to the wearer's body size and desired sitting position. Body weight is transferred into the floor through these adjustable elements. The exoskeleton weighs a mere 2.4 kg.

## New thermoplastic innovation center announced in the UK

Victrex plc (Thornton-Cleveleys, UK) is planning to increase its technology leadership in polyaryletherketone (PAEK) polymers with the construction of a Polymer Innovation Center in northern England. Financial assistance for the project includes US\$2 million in grant funding from the UK government's Regional Growth Fund, subject to satisfactory due diligence, which recognizes the vital, rapidly accelerating importance of high-performance polymers in the global marketplace.

"Victrex is continuing to invest in cutting-edge technological leadership in advanced polymers," says Victrex technical director Dr. John Grasmeyer. "Improved application performance at the same or reduced cost is a common objective that we're helping our customers to address across industries. The aircraft industry, for example, is now embracing newly developed technology for major cost and weight savings combined with accelerated assembly times. That's just one example among hundreds."

High-performance polymers based on PAEK, including polyetheretherketone (PEEK), are increasingly sought out for demanding applications in industry sectors that include consumer electronics, automotive, energy and medical. At the same time, Victrex is helping manufacturers to meet the need for demanding, more efficient processing techniques that reduce costs and speed time-to-market. In a fast-moving market that thrives on continuous R&D advances,

the planned Polymer Innovation Center will increase capacity to turn lab concepts and engineers' ideas into real-world solutions and processes that can sustain mass production. The facility will enable scale-up of new products and applications to full commercialization.

In 2014, Victrex invested more than US\$23 million — 6% of its sales — in R&D programs. This investment, together with UK government funding, is expected to build on that beginning, and help in the creation, directly or indirectly, of more than 80 jobs over the next 10 years and could ultimately see its total investment grow in value to as much as US\$24.6 million.

"This boost from the UK government's Regional Growth Fund is great news for Victrex, in enabling our company to continue pioneering the market for high performance polymers well into the future," says David Hummel, Victrex CEO.

Watch this YouTube video to learn about Victrex PEEK in a customer case study | [www.youtube.com/watch?v=ICXyQFvkBPg](http://www.youtube.com/watch?v=ICXyQFvkBPg).



Source | Victrex plc

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## ENERGY

## Believe it or not: The GE carbon fiber turbine blade turns 20

All the press the past couple of years about increased use of carbon fiber in commercial aircraft engines could give one the impression that its use there is recent, even novel. But the first commercial jet engine to make use of carbon fiber composite turbine blades was GE Aviation's GE90, certified in 1995. That's right ... two *decades*.

The GE90-powered Boeing 777s are among the most fuel-efficient and reliable commercial jetliners in history. With more than 2,000 GE90 engines delivered, the composite fan blade has become a landmark technology for GE and has influenced succeeding generations of GE commercial engines, including the GEnx and the new GE9X.

GE reports, however, that achieving certification of that first blade was no easy feat. "For our engineers, one of the biggest hurdles for the composite fan blade was understanding the characteristics of the new carbon fiber material," says Nick Kray, a consulting engineer for composite design at GE Aviation. "GE conducted hundreds of intensive tests on the new composite material to determine its breaking points. The results gave us enormous confidence in the composite material's durability."

To manufacture the blade, GE teamed up with Snecma of France to create CFAN in 1993, located in San Marcos, TX,

US. "CFAN has really perfected the production process for composite fan blades," says Kray. "At the start of production, the yield rate for composite fan blades was less than 30%. Today, CFAN has a yield of greater than 97%, and the business has doubled its fan blade production in the last five years from 5,000 blades in 2009 to 14,000 fan blades last year."

The next-gen GE9X will feature fewer and thinner fan blades than any GE widebody engine in service — 16 fan blades on its 3,404-mm front fan. For this, GE is designing a new blade, using next-generation carbon fiber composites. Almost 700 GE9X's have been ordered since the model was launched on the Boeing 777X aircraft last year. The first engine will test in 2016, with flight-testing anticipated in 2017. Engine certification is scheduled for 2018.



Source | GE Aviation

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## CW / MONTH IN REVIEW

Notes on newsworthy events recently covered at the CW Web site. For more information about an item, key its link into your browser. Up-to-the-minute news [www.compositesworld.com/news/list](http://www.compositesworld.com/news/list).

### Holding Company Composite opens carbon fiber plant in Russia

Russia-based plant will have 1,700-MT carbon fiber capacity in the Republic of Tatarstan. Additional lines could eventually total 10,000 MT or more.

03/16/15 | [short.compositesworld.com/HCCCFplant](http://short.compositesworld.com/HCCCFplant)

### Hutchinson composite suspension makes waves

French fabricator Hutchinson shows at JEC Europe 2015 an innovative front vehicle suspension, made with fiberglass/epoxy in a resin transfer molding (RTM) process.

03/16/15 | [short.compositesworld.com/HutchSus](http://short.compositesworld.com/HutchSus)

### Bombardier CS300 completes maiden flight

The composites-intensive CS300, a single-aisle jet that seats 100 to 149 passengers, joins the five CS100 aircraft already in testing.

03/02/15 | [short.compositesworld.com/CS300first](http://short.compositesworld.com/CS300first)

### Report forecasts healthy composites growth

MarketsandMarkets forecasts total value for the composites market of US\$90 billion by 2020, and says automotive composites will play a big role in growth.

03/02/15 | [short.compositesworld.com/MM-A350RF](http://short.compositesworld.com/MM-A350RF)

### Quickstep receives Nadcap accreditation

The company received Nadcap accreditation for composite special processing at its Bankstown Airport, Sydney facility.

03/02/15 | [short.compositesworld.com/QS-Nadcap](http://short.compositesworld.com/QS-Nadcap)

### FMG relocates to Cambridge, expands European operations

Following dramatic growth in 2014, Future Materials Group's new office in the DACH region will focus on market size and forecasting models.

03/02/15 | [short.compositesworld.com/FMGmove](http://short.compositesworld.com/FMGmove)

### Premium AEROTEC begins A350-1000 rear fuselage production

The Augsburg, Germany, supplier has begun carbon fiber and tape placement in the manufacture of the rear fuselage shell for the forthcoming A350-1000 XWB.

02/23/15 | [short.compositesworld.com/PA-A350RF](http://short.compositesworld.com/PA-A350RF)

### Report: Carbon fiber will be mainstreamed in automotive by 2025

Lux Research says R&D trends indicate carbon fiber composites will be poised to gain widespread adoption for automotive lightweighting.

02/23/15 | [short.compositesworld.com/LR-CF2025](http://short.compositesworld.com/LR-CF2025)

### Virgin Galactic opens LauncherOne design and manufacturing plant

This two-stage orbital launch vehicle will be manufactured at a facility near the Long Beach, CA, US airport.

02/16/15 | [short.compositesworld.com/VGL1plant](http://short.compositesworld.com/VGL1plant)

### Chomarat expands multiaxial glass fiber capacity

France-based Chomarat is expanding multiaxial glass fiber reinforcement capacity at its Tunisian plant to meet material demand for the wind turbine market.

02/16/15 | [short.compositesworld.com/ChomaratEx](http://short.compositesworld.com/ChomaratEx)

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## The “B” in BRIC should see a welcome economic boost in 2015

Globally, the “BRIC” countries (Brazil, Russia, India and China) continue to get composites industry press. But a financial health report on the Brazilian composites sector, released early in the year by the Latin American Composite

Materials Assn. (ALMACO, São Paulo, Brazil), indicates that 2015 could bring some relief to what was not a stellar 2014.

Brazilian composites sector revenues totaled US\$1.202 billion last year, down 0.1% compared to performance in 2013. In terms of volume, the decline was larger: composite molders

and fabricators consumed 2% less raw material, totaling 206,000 MT. These figures are part of the latest survey conducted for ALMACO by MaxiQuim (Porto Alegre, Brazil).

“We experienced interruptions and delays in investments in infrastructure from the federal government, which were added to the drastic fall in the transportation segment and

the lack of creativity and innovative power of the composites sector,” said Gilmar Lima, ALMACO’s president. (Lima, with mic in photo, is shown at the group’s annual Top of Mind event with ALMACO chapters presidents, left to right, from Argentina, Chile and Colombia.). “As for the revenue, some factors sustained this close tie with 2013, such as the generalized increase in costs and the uncontrolled price increase charged by one of the fiberglass manufacturers.”

With a 51% share, the construction industry, in 2014, remained as the top consumer of polyester composites, ahead of transportation (15%), corrosion (12%) and sanitation (5%), among others, totaling 151,200 MT. Wind power generation accounted for 90% of the demand for epoxy-based composites. The oil market ranked second, with 5%. In total, 54,800 MT were processed.

For 2015, however, MaxiQuim estimates a 2.4% revenue increase in the sector represented by ALMACO, totaling US\$1.231 billion and consumption of 207,000 MT of raw materials (+0.5%). “Even with the expectation of a bad year, some projects that benefit composites can no longer be postponed, such as those to be held to mitigate the water and energy supply problems,” says Lima. In the first quarter, therefore, the study estimates a revenue of US\$327 million, 4.5% higher than the revenue recorded in the first three months of 2014. For more, visit [www.almaco.org.br](http://www.almaco.org.br).



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### AUTOMOTIVE

## Globe Manufacturing at work on thermoplastic composites workcell

Globe Machine Manufacturing Co. (Tacoma, WA, US) told CW in an exclusive interview at JEC Europe 2015 (March 10-12) that it is adapting its RapidClave molding system for production of thermoplastic composite parts for automotive applications. The company is close to trial-ing a thermoplastic work cell process for production of structural automotive parts, said Globe president Calvin Bamford, Jr. The process is designed around unidirectional tape, will involve consolidation pressure and a combination of water and hot air for heat transfer, and should be unveiled sometime this year.

Read more about the new work cell | [short.compositesworld.com/GlobeTPWC](http://short.compositesworld.com/GlobeTPWC)

### CORRECTION

An alert reader of our March issue of CW noticed in our Focus on Design story p. 86 that we mistook, in the story headline, Auckland for the capital city of New Zealand. It is not. That honor, we were reminded, belongs to the city of Wellington. Our profound apologies to New Zealand's actual capital city and its inhabitants. CW regrets the error.

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## CARBON FIBER

### Australian carbon fiber industry collaboration

Australia's fledgling carbon fiber industry soon will be bolstered by a new partnership between Deakin University's (Burwood, VIC, Australia) Carbon Nexus Facility and DowAksa (Istanbul, Turkey). This partnership includes commitments to advance market adoption of carbon fiber composites, and promote Australian expertise in materials and manufacturing technologies to industrial composite parts makers and end-users in key export markets.

DowAksa, a joint venture between acrylic and carbon fiber producer Akrilik Kimya Sanayii AS (Aksa, Istanbul, Turkey) and The Dow Chemical Co. (Midland, MI, US), will work with Deakin's carbon fiber research center, Carbon Nexus, on collaborative R&D projects, professional development and exchange opportunities.

Deakin University vice-chancellor Prof. Jane den Hollander announced the move at the third biennial Carbon Fiber Future Directions Conference, hosted by Carbon Nexus, at nearby Geelong on Feb. 24. "Carbon Nexus, which we opened just nine months ago, was strategically positioned by Deakin University as the world's leading carbon fiber research center, directly tied to research and ready to work with industry on projects that will help drive the jobs of the future," she contends. "What we are announcing here, today, is a key step in the evolution of that strategy and demonstrates the critical role universities play in supporting local economies to reinvest and develop new economic bases."

Prof. den Hollander said the Deakin/DowAksa partnership initially would include collaborative carbon fiber research projects focused on catalyzing local demand for DowAksa carbon fiber, with eventual opportunities for adoption by industries globally. The Carbon Nexus pilot line will be optimized for the output of DowAksa carbon fiber samples to support the research projects, she added.

Carbon Nexus director Derek Buckmaster said the partnership is a key part of the growth plan for the research facility: "We are already

working in partnership with the world's first commercial maker of single-piece carbon fiber auto wheels, Carbon Revolution, which is based at our Waurin Ponds campus alongside Carbon Nexus." In addition to the wheel firm, Australian design engineering firm 36T will work on an advanced sports engineering project in partnership with the Deakin School of Engineering. And Quickstep Technologies (Bankstown Airport, NSW) is setting up a dedicated automotive division at Waurin Ponds campus to design and develop automotive manufacturing cells and enable the production of customer prototypes and initial production quantities, added Buckmaster.

DowAksa is a charter member of the Institute for Advanced Composites Materials Innovation (IACMI) consortium announced recently by US President Barack Obama to bring more than US\$250 million to bear on the development of the advanced composites industry in the US. Deakin University, already a member of the Oak Ridge Carbon Fiber Composites Consortium based in Tennessee, has expressed formal support for the IACMI and hopes it will provide an extended platform for collaborative engagement and networking with business and academic leaders in the American market.

See the YouTube video of the facility | [www.youtube.com/watch?v=khTFwYc7Rt8](http://www.youtube.com/watch?v=khTFwYc7Rt8)



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# PRSEUS update: Hybrid wing body passenger cabin takes shape

NASA calls on composites to enable a paradigm shift in future aircraft aerodynamics.

By Donna Dawson / Senior Writer Emeritus



**FIG. 1** Three-dimensional reinforcement

Dry 3D preforms were constructed and assembled to produce this HWB fuselage test section structure.

Source | NASA

» Since the day aviation innovators first imagined aircraft constructed of aluminum rather than wood nearly a century ago, the basic design of the commercial aircraft fuselage has been circular in cross-section. It has remained so because a cylindrical shape is considered the most economical way to build a fuselage with a pressurized passenger cabin, which permits comfortable, fast and comparatively fuel-efficient flight in the less dense air found nearly eight miles above the earth's surface. But the cylindrical paradigm is under assault by NASA's Environmentally Responsible Aviation group (ERA, NASA Langley Research Center, Hampton, VA, US). ERA is exploring new concepts for airframes to reduce weight and improve fuel efficiency, using advanced composite materials.

One paradigm shift is toward a hybrid wing body (HWB), a configuration defined by Dawn Jegley, ERA's senior aerospace

engineer, as the "general term NASA uses for all aircraft where the wing and fuselage are smoothed together with a flatter fuselage section to achieve a more aerodynamic shape." The passenger cabin, then, assumes a more box-like shape, with sidewalls that are flat, rather than curved (see "Learn More," p. 27).

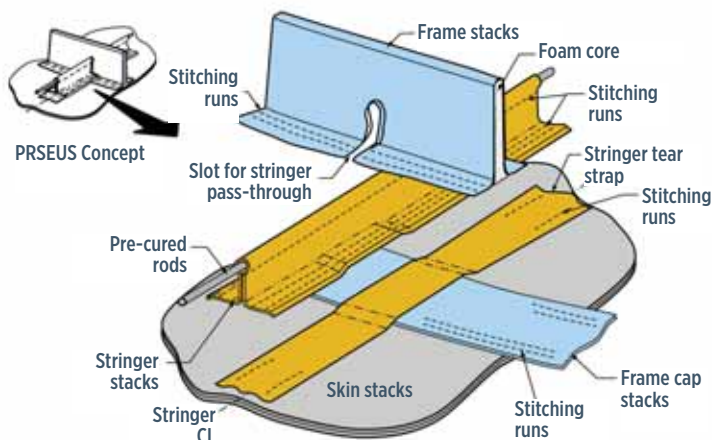
Since the HWB was announced publicly in 2011, ERA has been working on an innovative stitched composites approach to HWB aircraft (Figs. 1 & 2) as a way to produce a pressurized vessel in a noncircular shape. Known as PRSEUS (Pultruded Rod Stitched Efficient Unitized Structure), the project is now well underway, through a partnership with The Boeing Co. (Chicago, IL, US).

"The PRSEUS concept was born out of the need to significantly improve the structural efficiency and lower the manufacturing cost of composite primary structure for large transport aircraft," reported Patrick Thrash, an engineer/scientist at Boeing's

## FIG. 2 The preform, examined

An exploded view of the individual components that make up the preform assembly.

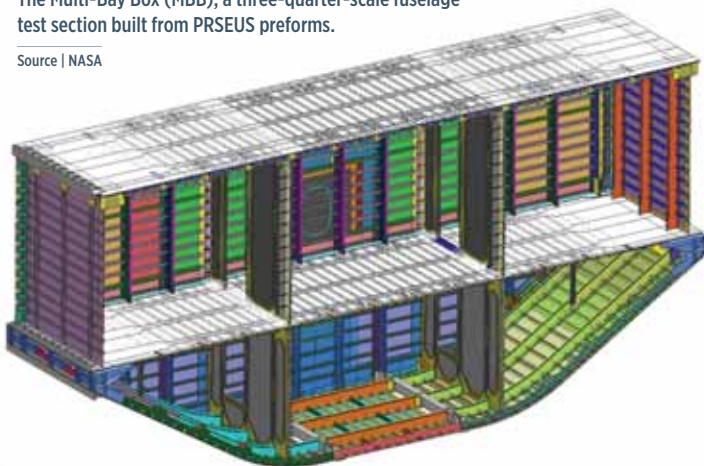
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## FIG. 3 CAD concept for subscale test section

The Multi-Bay Box (MBB), a three-quarter-scale fuselage test section built from PRSEUS preforms.

Source | NASA



## FIG. 4 Pultruded rods strengthen bulb stiffeners

Pultruded rods (below), with integral fillet features (shown at right) will be grit-blasted to prepare them for in-situ co-bonding, during resin infusion of the preform assembly.

Source | The Boeing Co.



California facility (Huntington Beach, CA, US), in his presentation on the subject at CAMX 2014 (Oct. 16-18, 2014, Orlando, FL, US).

## Long history, future hope

The need for a paradigm shift, however, was recognized much earlier. Jegley tracks the PRSEUS concept back to the early 1990s, when NASA worked with aircraft manufacturer McDonnell Douglas under the Advanced Composites Technology Program to develop stitched technology for future commercial transport aircraft wings. After Boeing bought McDonnell Douglas, the program continued, primarily with NASA funding. During this time, a 12.1m long composite stitched wing was built and tested. After the wing program ended, Boeing continued development of the stitched structure and added a pultruded rod through the stringer. When it was established in 2009, ERA selected the stitched structure as the primary structural concept for PRSEUS (see Fig. 2). The PRSEUS concept is taking shape as a 9.14m fuselage center cross-section (Fig. 3), known as a multi-bay box (MBB).

## Pultruded rod for strength and tooling

For PRSEUS, pultruded rods are used to strengthen the stringers, the longitudinal elements that reinforce the skin of a wing or fuselage, in the form of bulb stiffeners. "Bulb stiffeners are a different cross-section geometry from hat stiffeners, and have been used in aluminum airframes," Thrash explains. However, the use of a pultruded rod to enable a bulb stiffener is an original concept, unique to PRSEUS.

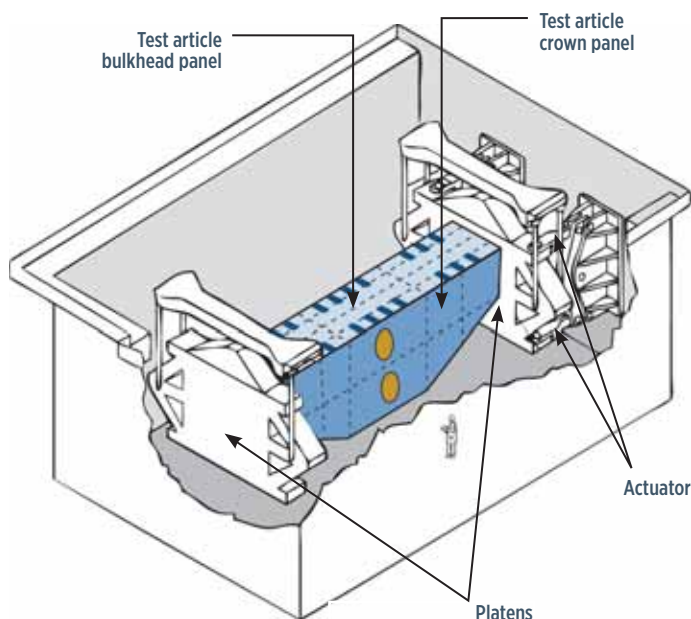
Thrash identifies the solid 9.5-mm diameter rods as Grafil 34-700WD standard-modulus, 24K carbon tow, from Mitsubishi Rayon Carbon Fiber and Composites Inc. (formerly Grafil Inc., Sacramento, CA, US) wet out by PUL6 amine-cured epoxy resin, developed specifically for this purpose by Applied Puleramic Inc. (API, Benicia, CA, US). Although the rods are circular in cross section, each rod has an integral fillet feature at its base. The rods were pultruded by Lawrie Technology Inc. (Girard, PA, US) through a precision steel die and cut to lengths up to 6m for shipment to Boeing Long Beach. There, Boeing postcured them at 177°C for two hours and then cut them to lengths for installation into the stringer preform for the test article panels.

## Stitched noncrimp fabric (NCF) preforms

The use of pultruded rods to strengthen airframe stringers is only one innovation in this clean-sheet design for airframe construction. Another is the use of infused oven-cured laminates rather than the conventional autoclaved prepreg historically used in most aerospace structures. Dry, noncrimp fabrics are used to build preforms for out-of-autoclave (OOA) primary structural parts, a technology that is also finding use in forthcoming conventional commercial »

**FIG. 5** Concept for MBB test regime

The MBB assembly, as it will be positioned in NASA's COLTS structural testing complex. Source | The Boeing Co.



aircraft (see "Learn More"). For the PRSEUS preforms, a multiaxial warp/knit noncrimp carbon fiber fabric was manufactured by SAERTEX GmbH (Saerbeck, Germany) by assembling HTS45 fiber from Toho Tenax Europe GmbH (Wuppertal, NRW, Germany) into a nine-ply construction ( $\pm 45^\circ/0^\circ/0^\circ/90^\circ/0^\circ/0^\circ/\pm 45^\circ$ ). These stitched, multiaxial fabrics — provided by SAERTEX in roll widths of 1.4m and 2.5m — are the building blocks of the preform that make up the panels for ERA's fuselage center test article.

The dry fabric construction is supported not only by the pultruded rods but also by foam-cored frame components (illustrated in Fig. 2, p. 23) that fit over the rod-stiffened stringer. The core is Rohacell WF110 closed-cell foam ( $110 \text{ kg/m}^3$ ) from Evonik Foams Inc. (Theodore, AL, US).

Thrash explains that these foam-cored support elements essentially served as tooling during subsequent resin infusion processing of the final preform assemblies. The stringer, frame, cap and skin elements were assembled into a near-net-shaped 3D preform for each panel and then were stitched together robotically, using one-sided stitching equipment supplied by KSL Keilmann Sondermaschinenbau GmbH (Lorsch, Germany).

Boeing used its Controlled Atmospheric Resin Infusion (CAPRI) process — its proprietary version of vacuum-assisted resin transfer molding (VARTM) — to infuse the preformed structure with Hexflow VRM34 resin, a two-part, amine-cured epoxy from Hexcel



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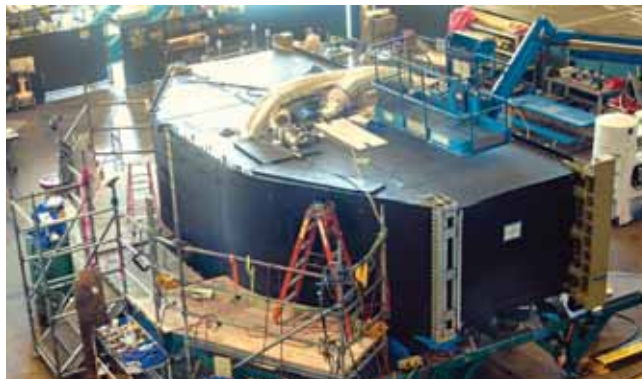
(Stamford, CT, US). It was oven-cured under vacuum at 93°C for five hours. After the bag was removed and the part cooled, the panels were postcured at 177°C for two hours.

Boeing assembled the three-quarter-scale, multi-bay fuselage structural test article at its Long Beach facility and the 9.14m wide, 4,536-kg MBB was shipped Dec. 12, 2014, via NASA's *Super Guppy* transport airplane, to NASA Langley (Hampton, VA, US). There, the MBB test article was instrumented and interfaced with NASA's Combined Loads Test System (COLTS) in March. The system can combine mechanical loads with internal pressure and thermal loads for testing large, curved panels up to 3m long and 2.4m wide, or cylindrical shell structures, such as simulated fuselage sections, up to 13.7m long and 4.5m in diameter (see Fig. 5, p. 24). At CW presstime, testing was to begin in April. At that point, the MBB will be pressurized to FAA specifications and subjected to flight-load conditions by applying bending loads for either tension or compression. "Bending loads and pressure loads will also be applied simultaneously," Jegley notes.

Jegley and Thrash make a strong case for cost savings compared to traditional prepreg composite construction, first by use of out-of-autoclave processing, thus eliminating the cost of autoclave operation. Next, dry fabric is faster and easier to lay up and eliminates the time and part-size constraints posed by the limited outlife of temperature-sensitive prepreg and the cost of waste

**FIG. 6** The MBB, in progress

The MBB box during assembly, with all panels in place. Source | NASA



prepreg. Because it facilitates large-part construction, use of dry fiber eases parts consolidation and thus eliminates assembly steps and cost. Additionally, the number and cost of mechanical fasteners and the time and cost required to drill holes and install them can be vastly reduced (panel-to-panel connections still require fasteners). Finally, the risk of structural weakness introduced by holes can be reduced. »



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## PRSEUS steps forward

Thrash concludes: "The manufacturing approach taken to fabricate the large, highly integrated composite panels and assemble them into the multi-bay fuselage structural test article has proven extremely successful."

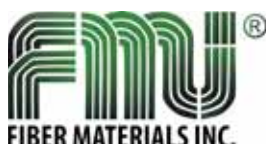
He proposes that the next step forward is automation and industrialization of the processes to achieve the production rates necessary for commercial aircraft construction. Moreover, new tooling designs and next-generation materials that will improve on those currently used in the MBB now under preparation for testing must be determinedly pursued. In terms of materials, says Thrash, the project must aggressively target noncrimp fabrics with functional interlayers and toughened resin systems. Finally, he urges the "implementation of the technology onto an actual piece of flight hardware" as the means to "obtain experience, build confidence and gain acceptance by program management for broader use on future airframe applications."

Implementation of PRSEUS on commercial aircraft, however, is not expected before 2025. Man-rated commercial flight innovations necessarily consume many years of development, testing and qualification to protect the flying public and military personnel. But in this case, there is precedent for success, in the so-called flying-wing design developed by Northrop Grumman (Falls Church, VA, US) for its *B2* bomber, and in Bombardier's dry fabric, OOA wing construction for its new *CSeries* regional jet. Reduced manufacturing cost and better fuel efficiency clearly are goals airframe OEMs are pursuing and outcomes airlines and military procurement agencies can all embrace. The concept is, therefore, not only intriguing, but will probably prove to be both doable and worth doing. **CW**



### ABOUT THE AUTHOR

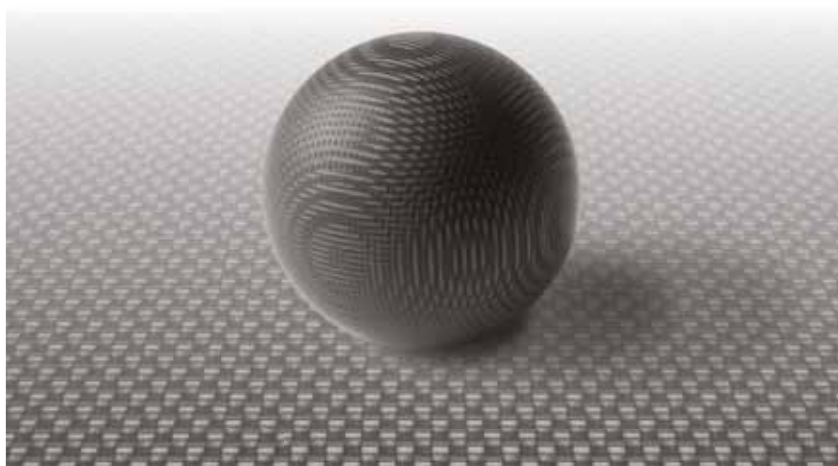
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## Weber Manufacturing Technologies: Midland, ON, Canada

**With a long, storied history in composites moldmaking, this rare nickel vapor deposition specialist has built a strong niche, making large, high-quality tools.**

By Jeff Sloan / Editor-in Chief

» Moldmaking for composites fabrication applications is a decidedly immature segment of the overall toolmaking sector. Molds used by injection molders, for example, are provided to them by a highly developed and global network of tooling suppliers. The molds, the materials used to make them and the methods by which they are made are established, tried and true. By contrast, the molds used for composites manufacturing are, more often than not, fabricated in-house and employ various methods and materials that can range widely from Invar, steel and aluminum on one hand, to wood or foam or more familiar ground, a composite. There are, however, those who specialize in moldmaking. And few moldmakers in the composites marketplace have established a stronger position in this specialty than Weber Manufacturing Technologies.

Weber stands out from the majority of moldmaking specialists, however, by way of a secondary specialty — nickel vapor deposition (NVD) — that has helped it carve out a niche few other manufacturers in the world can claim. NVD enables Weber to fashion molds for unusually demanding, high-performance composites applications. CW paid a visit to Weber's facility in Midland, ON, two hours north of Toronto on the shore of Georgian Bay, to learn more about the company and how NVD has propelled the company to a distinctive position in the composites toolmaking community.

### How it all began

Weber Manufacturing's founder and namesake, Reinhart Weber, opened a tool shop in Windsor, ON, that, in 1962, served primarily the automotive industry. In 1967, he moved his business to Midland to be closer to his second home in an area around Midland known colloquially as "cottage country."

By the late 1980s, with business expanding into other markets, Weber identified a need for higher quality nickel shells for kitchen sink mold applications in Europe. Conventional nickel shells were made by electroforming, a slow, galvanic process in which a master shape is placed in

### ■ Composites moldmaking specialist

Weber Manufacturing Technologies' main plant in Midland, ON, Canada houses most of its moldmaking, machining and finishing operations, producing nickel-shell, steel, aluminum and Invar tooling for composites manufacturers worldwide.

Source | Weber Manufacturing Technologies



a tank as a cathode and nickel is gradually plated over many weeks. Weber eventually connected with a nickel-mining company north of Midland, which uses nickel vapor deposition (NVD) to create and refine nickel pellets and powders for, amongst other products, stainless steel. The technology fit well with Weber’s desire to develop what is essentially an *additive* manufacturing process that minimizes waste. “Almost two years were spent designing and refining the process and apparatus to facilitate depositing nickel on solid, CNC-machined master shapes,” says Tom Schmitz, Weber’s business manager – composites.

In 1989, Weber established its Nickel Tooling Technology (NTT) Division, and in 1991 it sold its first NVD nickel shell to Schock GmbH (Regen, Germany), which used it in a mold to produce a composite (granite/quartz/PMMA resin) sink. In 2000, Weber established its NVD Nickel Division and its own NVD operations onsite in Midland. In 2001, the company produced the first molds using its own NVD technology — dozens used to fabricate interior parts for automaker Mercedes-Benz (Stuttgart, Germany).

The launch of the new technology was not trivial, Schmitz recalls, and exposed Weber Manufacturing to much risk and uncertainty. “If that nickel plant did not work, we would have been in a nondelivery position,” he says. “So, it *had* to work.”

And work it did. And still does. Today, Weber has positioned itself as a fabricator of large, high-quality tools of not only nickel but steel, aluminum and Invar — notably, for very large composites molding processes. “We stay away from the small stuff,” Schmitz notes. Processes include injection, compression and resin transfer molding (RTM) as well as sprayup, slush molding, resin infusion and autoclave cure. The company continues to focus on work in its seminal automotive sector as well as the construction and aerospace markets. In addition to Schock and Mercedes-Benz, Weber’s customer list is replete with recognizable names: DuPont, Fritzmeier, Boeing, Albany International, Zodiac Aerospace, Bell Helicopter, GE Aviation, GKN Aerospace, CTL Aerospace, Gurit Automotive, Ford, Chrysler, GM, BMW, Aston Martin and many others.

In 2008, Weber launched an ancillary business, called Master-Grain, which uses the NVD process to manufacture a full line of

durable composite residential doors and entryways. NVD’s strength here is its ability to make a mold that replicates, in great detail, a wood’s grain and texture, right down to the knots and swirls that characterize a real wood door.

**NVD: How it works**

Because NVD is so central to all that Weber does, it seemed only right that the CW tour start there, with Schmitz as our guide. Weber’s facility in Midland

fills two buildings. The larger (12,542m<sup>2</sup>) is where most of the employees work and most of the moldmaking is done (opening photo, p. 40), including machining and finishing. NVD operations, however, are performed in the other building, just a stone’s throw away. Although it is smaller, at 3,251m<sup>2</sup>, it is home to an uncommon sight — four large, steel cylindrical chambers (Fig. 1) fed by a tangle of tubes and ductwork, all monitored 24 hours a day, seven days a week by »

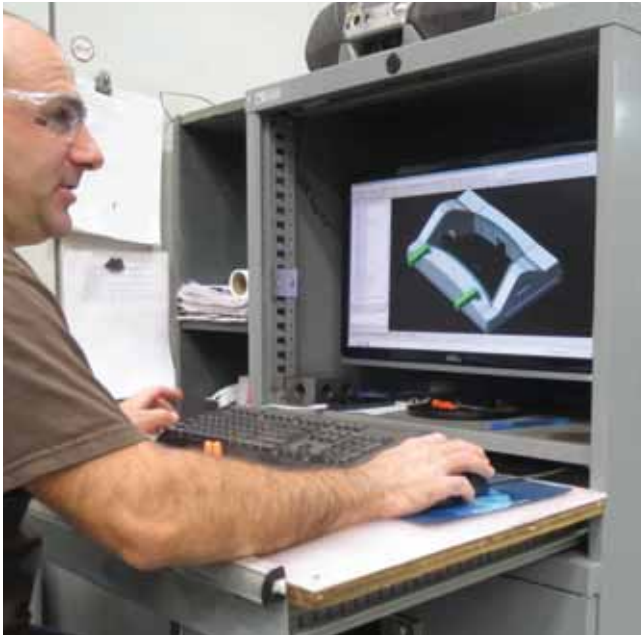
**FIG. 1 Toolmaking distinctive: NVD**

The smaller of Weber Manufacturing’s two buildings houses the means by which it has made its largest moldmaking impact. Pictured at right are three of the company’s four nickel vapor deposition (NVD) chambers. NVD is rarely done in moldmaking, and Weber is one of the few companies in the world to do it at all.

Source | Weber Manufacturing Technologies

Source | CW / Photographer | Jeff Sloan

TABLE 1 Moldmaking Material Properties Comparison					
Material	Units	P20 tool steel	Aluminum	Invar	NVD nickel
Density	kg/m <sup>3</sup>	7800	2720	8130	8910
Yield strength	MPa	990	55	276	411
Stiffness	GPa	205	70	145	114
Thermal expansion	mm/mm (°C)	12.6x10 <sup>-6</sup>	23.6x10 <sup>-6</sup>	1.3x10 <sup>-6</sup>	13.1x10 <sup>-6</sup>
Thermal conductivity	W/m (°C)	29	210	11	88
Hardness	Brinell	270-480	20-160	120-180	330-380



**FIG. 2** Multiaxis machining a mainstay

The company maintains 22 multiaxis CNC-machining centers. Here, a technician operates one of Weber's six 5-axis machining centers. He and other operators have direct digital access to all designs via machine-side computers.

Source (this and all following photos) | CW / Photographer | Jeff Sloan



**FIG. 3** Roughcutting the basic shapes

This system from Ingersoll Machine Tools (Rockford, IL, US) is used to rough out mold bases and mandrels and is among the most frequently used machining centers at the Weber plant.

Weber employees ensconced in an adjacent control room, separated by large glass windows that provide a view of all of the facility's machinery and equipment.

Inside, Schmitz begins the NVD tour by noting that the process is often compared to electroforming. But he points out that NVD's advantages are both simple and substantial: NVD is faster ("We can produce nickel 20 times faster than electroforming"), produces a much more uniform tooling surface, is excellent at replicating finely detailed mold textures and surfaces, produces negligible residual stress, is weldable *and* is 99.9% pure. Schmitz says that a new NVD mold can be fabricated from an existing deposition mandrel in just two to three weeks and can be 3 mm to 30 mm thick, whatever is required. Similarly, multiple identical replacement molds can be manufactured from the same master. Nickel also offers good thermal conductivity, easy mold release, 330-380 Brinell hardness and high density (see Table 1, p. 29).

If this is the case, why don't more moldmakers use NVD to make tools? Schmitz says the simple answer is that NVD is anything but simple: "The materials, chemicals and temperatures involved are complicated and very specialized," Schmitz notes. "It took us 10 years to develop and refine the process to where it is today."

The trick is in vaporizing nickel, which is a complex, multi-step process used to commercially refine high-purity nickel. Weber starts, says Schmitz, by combining nickel and carbon

monoxide (CO) to create nickel tetracarbonyl, or  $\text{Ni}(\text{CO})_4$ . That compound is passed through a reactor and a condenser to create liquid carbonyl, which is then vaporized and injected into one of the four large, purged, sealed, steel chambers at the center of the NVD facility. Inside the chamber is the aluminum or steel mandrel that is designed for nickel deposition. The mandrel, onto which the nickel is deposited, is heated to 180°C; as the carbonyl enters the chamber, the nickel adheres to the hot surfaces only, building up on the tool surface at a rate of 0.25 mm/hr. Carbon monoxide is liberated as the nickel deposits onto the mandrel and is then recycled out of the chamber. (Weber says the air coming out of its stacks is breathable.)

Schmitz leads us to one of the chambers where we peer inside through a small porthole. The chamber interior is lighted and the mandrel is easily visible. The vaporized nickel is colorless, but assumes a silver-grey hue as it deposits onto the mandrel. Not all surfaces on the mandrel need nickel, so some sections are masked off

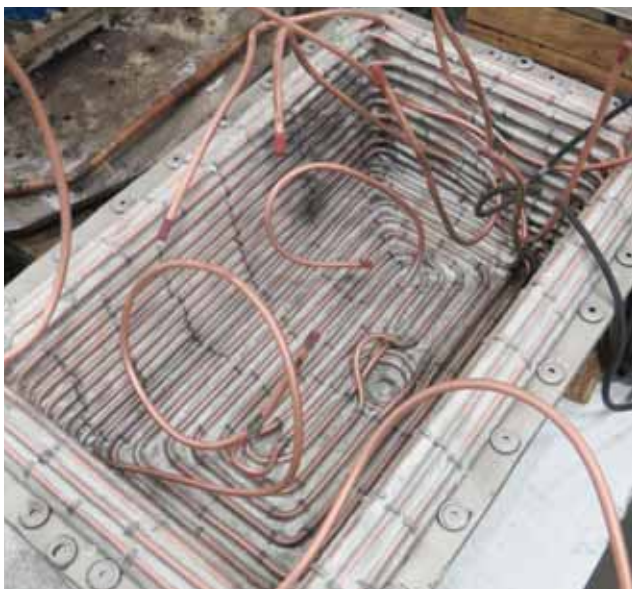
or cooled to resist nickel deposition. Further, to prevent nickel from adhering to the chamber interior, the chamber itself is kept comparatively cool (60°C), which makes it warm but not hot to the touch. A typical mold for an automotive exterior part, Schmitz says, will be designed with a nickel shell up to about 10 mm thick, which takes only 40 hours to build. Typical aerospace molds for autoclave-cured parts are 7 mm thick.

Why don't more moldmakers use NVD to make tools? The simple answer is that NVD is anything but simple.



**FIG. 4** Complex heating/cooling systems

Weber is well known for the conformal steel and copper heating and cooling systems on its molds. Here, technicians shape steel tubing through which hot oil will flow to heat the back, or B-side, of a nickel-shell tool face.



**FIG. 5** Putting the pipe in the proper places

The B-side of this sink mold shows formed copper heating and cooling lines arranged, soldered together and in the process of attachment in conformity to the tool's surface.



**FIG. 6** Nickel shells for autocomposites

A Weber technician hand-finishes a nickel-shell mold for an automotive application. Nickel is attractive for automotive applications because of its Class A capabilities, its ability to replicate fine details and its minimal residual stress.



**FIG. 7** Still serving the unsinkable sink market

Reinhart Weber began making molds for residential and commercial sink manufacturers in the 1980s and saw NVD as a good alternative to electroforming. Weber still serves the sink market today, including for DuPont's Corian line.

He also reports that Weber has developed CAD modeling software that enables engineers to accurately calculate part surface area. The nickel shell thickness requirements are determined by pressure and the surface finish of the final part. "The only way to control shell thickness is deposition time," says Schmitz.

Nickel shells that come out of the NVD process are highly uniform but their surfaces are not yet ready to produce parts. Separated from the mandrel, each shell moves to Weber's main plant for further preparation. There, we move as well.

### Main plant tour

The tour of the primary facility at Weber starts in the machining department where Schmitz repeats a sentiment heard in many

such shops: "If we're not making *chips*, we're not making money." Schmitz says that usually Weber's 5-axis machines — six of the company's 22 total machining centers — run about 23 hours per day. The size and type of machining center varies (see Figs. 2 and 3, p. 30) and includes units from DMG (Deckel Maho, Davis, CA, US), Makino (Mason, OH, US), Tarus (Sterling Heights, MI, US), Kuraki (Niigata, Japan), SNK (Osaka, Japan), Ingersoll Machine Tools (Rockford, IL, US) and Droop+Rein (Bielefeld, Germany). In addition, the company is planning to add another very large 5-axis machining center.

Notably, Weber's machining environment, says Schmitz, is nearly paperless. Operators interact with CAD files and develop CAM programs via machine-side computers, which provide



**FIG. 8 Residential construction: wood replication**

Weber's MasterGrain business uses NVD tooling to replicate wood grain in compression molded sheet molding compound laminates for sandwich-panel residential doors and entryway components. The image at right shows the level of enabled detail.

access to all designs and the job queue. It's here that much preliminary mold-making work is done, roughing out cores, cavities and other tool components.

The mold materials depend on the customer, the application and the process. It can be steel, aluminum, stainless steel, Invar or nickel, or a combination of the above. If nickel is the choice, which it is approximately 30% of the time, Weber will deposit a nickel shell on a mandrel, strip it from the mandrel and then mount it on a welded, egg-crate-style backing structure of steel plates. The robustness of the design depends on the molding process. The thickness and pitch of these components are sized to handle the molding pressures and clamp tonnage of the molding process.

What happens to a mold next depends on the process for which it's intended. Out-of-autoclave molds, which require integrated heating and cooling capability, are sent to Weber's mold tubing fabrication area, adjacent to the machining area. The company, notes Schmitz, is well known for providing highly contoured, highly efficient molds using conformal heating and cooling tubes. These tubes help optimize mold heating and cooling and provide uniform temperatures across the mold face. These steel or copper lines, designed to carry hot oil, are shaped to match the back, or B-side, of the nickel shell and then are attached via a variety of soldering or filled epoxy methods (Figs. 4-5, p. 31). Many molds at Weber, says Schmitz, are supported in a mold frame; the frame includes an integrated manifold system for hot-oil distribution. The tubing circuits attached to the backside of the mold are then connected to the manifold after the mold is placed into the frame.

Finally, all molds are sent through Weber's coordinate measuring machine (CMM) for dimensional verification and

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quality control, using a DEA Delta Slant machine (Hexagon Metrology, Stockholm, Sweden). Any dimensions that exceed tolerance are re-machined or worked by hand to bring the mold into compliance.

We are shown next into Weber's NVD master model room, home to automotive instrument panel, door, console and other master models of auto interior components. Textured auto interior molds have become a robust business area for Weber. These master models, says Schmitz, are "stored on site and allow us to quickly replace a mold whenever needed." The masters are used to fabricate new NVD nickel molds and are exact replicas of the original.

The final tour stop offers a glimpse of Weber's building and construction business. Nickel's ability to polish to a high

them, over the life of a home, more cost-effective.

### The future is bright

Weber is currently the only fully integrated, custom moldmaker with nickel-shell toolmaking capability.

Its presence in automotive, aerospace and building and construction arenas, says Schmitz, helps even out the peaks and valleys associated with each industry. As a result, this toolmaker has established a unique and, by all measures, secure link in the composites supply chain. **CW**



### ABOUT THE AUTHOR

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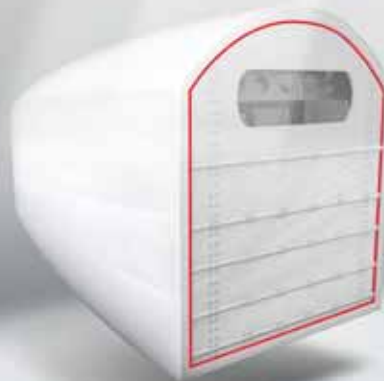
finish, and to replicate fine surface textures, makes it ideal for kitchen and bath sink molding, as well as bathtub fabrication (see Fig. 7, p. 31). Weber provides all of the molds used by DuPont to manufacture its Corian-brand shaped products. Schmitz says DuPont had, at one point, planned to move its Corian moldmaking operations to Mexico due to substantial postmold trimming and other work required by the company's aluminum molds. Since switching to Weber's nickel-shell tools, he says, DuPont's postmold work is minimal and DuPont was thus able to avoid moving work to Mexico.

Here, its MasterGrain line of doors also benefits substantially from nickel's ability to replicate in tools a variety of wood grains and textures (Fig. 8, p. 32). These tools are used to compression mold sheet molding compound (glass/polyester) to fabricate composite laminates, which are then used to assemble a full line of tough, weather-resistant residential entry doors. Schmitz says MasterGrain doors are superior to the natural wood versions they replicate, because their durability, their ability to hold color and their natural look and feel make

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## Ascent Tooling Group Ascends via Innovation

**The world's largest metal and composite moldmaker has a new name and continues to make a name for itself in closer control of large-part dimensional tolerance.**

By Sara Black / Technical Editor

» As the composites industry has grown, so have its toolmaking specialists. A case in point is the Ascent Tooling Group. Part of AIP Aerospace (AIPA, Santa Ana, CA, US). Up from 600 to 900 employees and reaping annual revenues of US\$200 million in just five years, it is reportedly the world's largest aerospace tooling provider.

Formed in 2012 when American Industrial Partners (AIP) purchased the US holdings of Hampson Aerospace, AIPA includes three well-known aerospace tooling-related companies: Coast Composites (Irvine, CA, US), Odyssey Industries (Lake Orion, MI, US) and Global Tooling Systems (GTS, Macomb Township, MI, US), as well as aerospace part fabricators Textars (Grand Prairie, TX, US) and Composites Horizons (Covina, CA, US). In September 2014, the Ascent Tooling Group was formed, which more fully integrates Coast Composites, Odyssey and GTS.

"Combined, these companies offer our customers the widest set of capabilities, full vertical integration to control cost and schedule, and the largest capacity in the industry," asserts Paul Walsh, Ascent's president and COO. The group produces metal and composite tools ranging in size from small to some of the largest and most complex tools in the industry, for manufacture of composite fuselages, wings, frames and stiffener parts. The Ascent Tooling Group has supplied molds for virtually all major aerospace composite programs, most recently the tooling for more than half of the Airbus (Toulouse, France) A350 XWB's outer surface, including the forward fuselage, wings, center wingbox and sections of mid- and aft-fuselage as well as stringer, frame and nacelle tools. Invar was the choice for the cure tools, with steel or aluminum selected for trim tools and other tool types. Ascent also is



### ■ Impressive toolmaking combination

Ascent Tooling Group is the world's largest aerospace tooling provider. The group builds more Invar tools, such as these massive wingskin tools shown here, than any other moldmaker, and consumes in excess of 1 million kg of the iron/nickel alloy per year.

Source (all photos) | Ascent Tooling Group

(at both Coast Composites and Odyssey) its own sophisticated system to compensate for real-time temperature changes within the tool materials during machining. Accuracies reportedly can be maintained to  $\pm 0.254$  mm on tool structures up to 20m or more in length. Further, all of Ascent's CNC machines include internal cooling systems to prevent heat-induced "growth" of the machine's metal parts during long hours of operation.

"On a 10m-long steel tool, a temperature swing of 10°F can be enough to throw the tool out of spec, and 10° swings are common even in air-conditioned factories," explains Walsh. On-machine inspection is another key piece of dimensional control, by means of inspection probes and software from Renishaw plc (Gloucestershire, U.K.) installed on each machining center (see "Learn More").

Tight tolerances are especially critical on Invar tools, because Invar is selected precisely for its ability to maintain dimensional accuracy during part processing. "We build more Invar tools than anyone," Walsh contends. Ascent Tooling Group reportedly buys more than 1 million kg per year of the iron/nickel alloy, prized for

its very low coefficient of thermal expansion (CTE), which is close to that of carbon/epoxy prepreg. Its relatively high cost means Invar is typically chosen for performance-critical production tools, with more complex shapes.

To enable transport of the more enormous Invar tools — for example, the wingskin tools for the Airbus A350 XWB in Illescas, Spain (see "Learn More") — tools must be modular. "The tool is designed, fabricated and machined in modular sections

around typical transportable sizes," says Walsh. "Shipping is a logistical test." Indeed, Walsh has many tales of tool shipments via multiple transportation modes, including a rush transport that involved the massive Antonov An-225 cargo plane. But after tool segments are delivered to a customer via truck, ship or air transport, the very real engineering challenge, he maintains, is joining "the finished sections together to maintain both accuracy and vacuum integrity."

For that, Coast Composites' has developed its patented "deep penetration" laser welding, which joins Invar facesheets. In preparation, tool modules are brought together, aligned as closely as possible using alignment features and then dimensionally verified. The backup structure is welded first, using traditional arc-welding technology. Then, a traveling welding robot laser-welds the seams »

### ■ Temperature control key to part tolerance

At Ascent, control of CNC-machining practices is critical to maintaining tight dimensional tolerances in tools and the resulting molded parts. Control strategies include compensation for real-time temperature changes within the tool materials during machining and on-machine inspection via probes and software from Renishaw plc (Gloucestershire, U.K.).

involved in major tooling programs for The Boeing Co.'s (Chicago, IL, US) 787, 737 and 777, the Lockheed Martin (Ft. Worth, TX, US) F-35 and Northrop Grumman's (Falls Church, VA, US) share of the F-18, among others (see "Learn More," p. 37).

### Modular metal tools with dimensional accuracy

The company's growth reflects its focus on maintaining best operational practices that result in very accurate tools. If part accuracy requirements are 1.27 mm, for example, the tool must have a dimensional accuracy of 0.64 mm or less. "The tool has to be more precise than the part itself," says Walsh. Maintaining that kind of accuracy over a large expanse of metal tool face is very difficult, but the company has developed operational strategies to cope. To ensure tight tolerances, Walsh says Ascent has developed



### ■ Low-temperature cure controls cost

This production composite tool was made with carbon/epoxy cured at relatively low temperature, then subjected to a freestanding postcure at up to 200°C. This relatively low-temperature curing regime allows for the use of more cost-effective master materials, which reduces overall tool cost.



### ■ Carbon/BMI for high-rate tools

For high-rate composite production tooling, a carbon/bismaleimide (BMI) material combination is typically specified. A carbon/BMI tool is shown here, after postcure, as it is machined to final tolerance.

between the Invar facesheets as it travels the length of each seam/joint. According to Walsh, the very narrow focus of the laser beam minimizes the heat-affected zone and the process speed does not cause distortion or shrinkage of the metal. The process requires neither filler metal nor post-weld heat treatment. "We've done 72 laser-welded joints on critical wing tools over the past seven years with no vacuum leakage," Walsh claims.

### A variety of composite tools

On the composites side of the house, relates Tim Shumate, AIPA's director of business development, the company consolidation has resulted in a composites "center of excellence" at Coast's Santa Ana location that includes ample cold storage, a 4m by 15.2m autoclave, large oven, automated cutting machine and more. Coast's composites group has developed tooling solutions for both prototype and production composite tools from a wide palette of materials and processes. "Sometimes, I think our industry doesn't promote composite tools strongly enough — they offer many benefits," Shumate contends, pointing out, "They heat up quicker than a metal tool because of lower thermal mass, which means you can turn your part quicker, thus creating more autoclave capacity, in theory. This can be key on a high-rate program, since it lowers capital costs."

Another driver for composites is weight. Shumate describes Coast's massive fuselage tool for Boeing's 787, produced using carbon/bismaleimide (BMI) material from Cytec Aerospace Materials (Tempe, AR, US) as a series of machined segments that, when assembled, formed the barrel over which fuselage sections 47/48 were fiber-placed. The high-temperature-capable tool has performed well, and was designed for production cycles at temperatures and pressures up to 177°C and 6.89 bar.

"On the 787 tooling, the rotational mass of a large fuselage tool used in a fiber placement machine would have been a problem if made with Invar. Tool mass can also be a factor in moving the tool through a shop," says Shumate.

Composite tooling also can reduce overall tooling cost for rate tools because multiple additional tool copies can be pulled from the original master. Each metallic tool, on the other hand, must be remade at the same cost as the original. Shumate elaborates: "A composite tool has several cost components: the master, the facesheet, the backup structure and finishing/machining. The material suppliers are focused on the facesheet. We are looking at the cost of all of the components, to get a better total cost reduction."

Coast Composites is in the process of evaluating new tooling materials. "For rate production tools, used to cure 177°C structural parts, BMI has the history and proven performance, and as a result has been the preferred material for years," says Shumate. That said, BMI's out life and handling could be improved. And although BMI tooling material suppliers are addressing these issues in the near term, and making good progress, Shumate says Coast is looking into an alternative, benzoxazine, from Henkel Corp. (Bay Point, CA, US), which is prepregged and distributed through Airtech International Inc. (Huntington Beach, CA, US, see "Learn More").

Other alternatives include Cytec's BMI DForm tooling prepreg, a slit fabric prepreg that reportedly improves conformability and reduces layup time by 75% yet delivers a high-quality surface finish; CFOAM carbon foam from Touchstone Research Laboratory Ltd. (Triadelphia, WV, US); and lower-cost, optimized tool infusion processes.

### Capital investment, turnkey future?

Ascent Tooling Group employs many machining centers from many suppliers, including Henri Liné (Granby, Quebec, Canada) and Handtmann CNC Technologies (East Dundee, IL, US). It recently committed US\$20 million to purchase eight

automation. "We recognize that many of our customers are looking for a total manufacturing solution, beyond simply a tooling solution," says Brian Williams, CEO of AIPA. "Linking full-line integration and factory automation with our tooling technology allows us to provide unique solutions that greatly streamline aircraft manufacturing." **CW**



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new high-speed gantry-type units from Parpas America (Bloomfield Hills, MI, US).

Ascent Tooling Group's sister entity, the Ascent Integration & Automation Group, combines automated drill and fastening system specialist Brown Aerospace (Kimball, MI, US), the advanced systems division of waterjet specialist Flow International, now Flow Aerospace (Jeffersonville, IN, US) and Ascent Integration, which is dedicated to factory and assembly line integration. This group will leverage Ascent Tooling Group's fabrication and assembly-jig expertise to offer customers integrated, turnkey assembly line designs and factory



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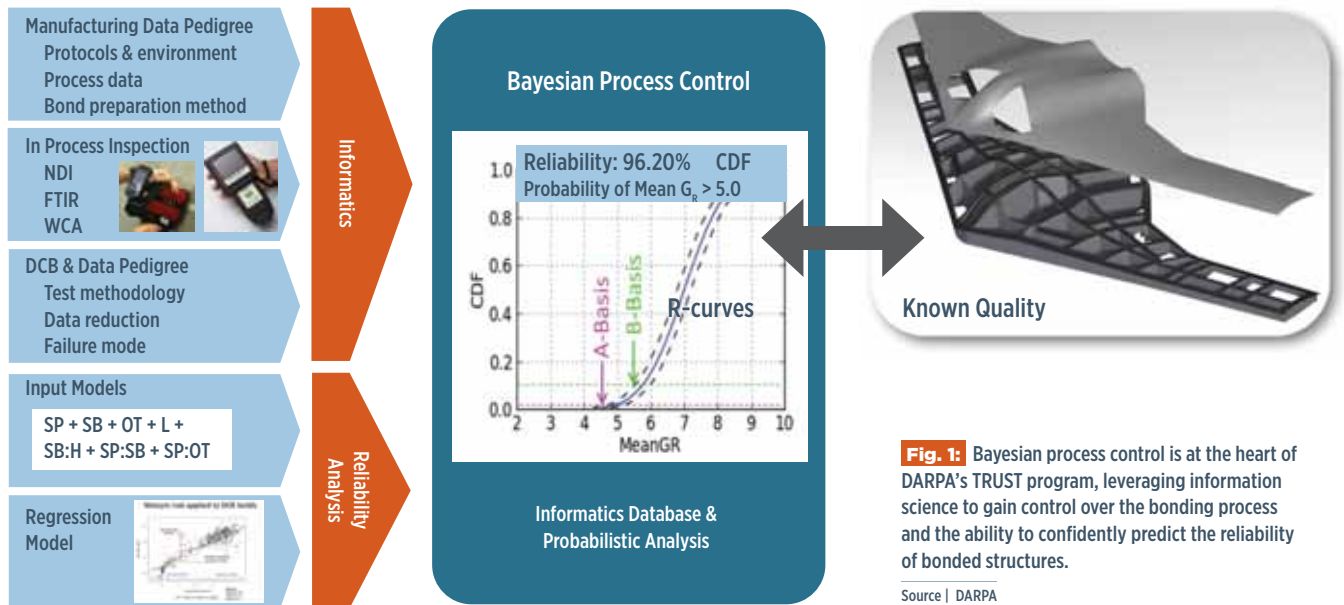
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# Building TRUST in bonded primary structures



**A DARPA program aims for certification via a Bayesian process control system for the factory floor, bounding uncertainty and predicting reliability in real-time.**

By Ginger Gardiner / Senior Editor

» Unitized, adhesively bonded composite primary structures on aircraft could offer substantial cost savings by dramatically reducing part and fastener counts, as well as time and labor for airframe fabrication and assembly. Lockheed Martin Skunk Works (Palmdale, CA, US) demonstrated the possibilities in 2009, during development of the Advanced Composite Cargo Aircraft (see “Learn More,” p. 42), with a 90% part count reduction in its bonded composite fuselage and vertical tail. But redundant mechanical fastening is currently required for certification of adhesively bonded primary structures on military and commercial aircraft (see “Learn More”).

Lockheed Martin Aeronautics Co. (LM Aero Palmdale), however, now leads the Transition Reliable Unitized STructure (TRUST) project, part of the Defense Advanced Research Projects Agency's (DARPA, Washington, DC, US) Open Manufacturing (OM) program. An effort to reduce cost and speed delivery of high-quality parts with predictable performance for defense systems, OM seeks to do so by reducing the uncertainties that cause cost overruns and delays during development, testing and early production. The purpose of TRUST is to develop the manufacturing process control necessary for certification of unitized bonded composite primary structures without redundant fasteners. “The goal is bonded primary structure,” says Skunk Works program manager Brad Hanson, “but no one is yet confident we can eliminate bad bonds.” In response, TRUST is taking a Big Data approach, attempting to build such confidence through Bayesian process control (BPC). “The overall goal is to create a framework that captures factory-floor variability and leverages probabilistic computational tools to characterize and reduce the risk of manufacturing technologies — in this case, bonded composite structures,” says Mick Maher, DARPA program manager.

## What is Bayesian process control?

The virtue of BPC is that it avoids the incredible mathematical complexities of modeling every aspect of an extremely variable process — in this case, manufacturing bonded composites. Instead, BPC models measurable data. The basic concept is to collect data from the manufacturing floor and use it to predict the reliability of the final bonded structure. This begins through what Hanson calls an “informatics data warehouse” — essentially a state-of-the-art database that permits ready access to all data for engineering analysis. Early testing is performed to develop models that describe the bonding process variables and relate these to changes in bond performance. These models are then coupled with advanced statistical methods to characterize process variability. Such predictive models continue to mature with additional data input and reveal which process variables are critical to control. The goal is not to eradicate uncertainty but to continuously refine its boundaries until uncertainty is a quantified entity that can be addressed (see “Learn More”).

Once models are thus refined and the BPC system is deployed to the factory, bonding process reliability is calculated based on real-time manufacturing process input. “What’s more,” says Hanson, “this Bayesian process control is a *learning* system, so that the more parts we build and test, the better the predictive model gets.”

## Building the BPC models

To build a model that could predict how changing process variables impact the bonded structure outcome, it was necessary to design experiments that explored the possible changes in these variables. Double cantilever beam (DCB) testing is a popular method for evaluating the toughness of bonded joints. TRUST modified the method (ASTM D 5528-01) for determining opening Mode I interlaminar fracture toughness ( $G_{Ic}$ ) — which classically is not bonded — so that coupons consisted of two bonded laminates with a nonadhesive insert placed between them to form an initial crack. This proved especially sensitive to bond quality resulting from the manufacturing process. However, the TRUST Phase I budget for model development was limited, so it was important to design the experiments to learn as much as possible from a small data set. To efficiently test three to five levels of seven critical bond process variables, therefore, subcontractor Southwest Research Institute (SwRI, San Antonio, TX, US) and Lockheed Martin designed several sets of experiments that would extract high-confidence data from only 100 DCB panels, each yielding six test coupons. Using this design of experiments (DOE) approach — as opposed to full factorial experiments — reduced the total number of DCB tests from 21,870 to 600.

DCB specimens comprised a “green” uncured laminate and adhesive that were co-cured to a pre-cured laminate. The laminates were made from Cytec IM7/MTM45-1 unidirectional prepreg tape and the adhesive was Cytec FM309-1 (Cytec Aerospace Materials, Tempe, AZ, US). A thin insert made from fluorinated ethylene propylene (FEP) separator film was placed between the pre-cured laminate and the adhesive so that the crack initiated at the site of interest, which is that interface.

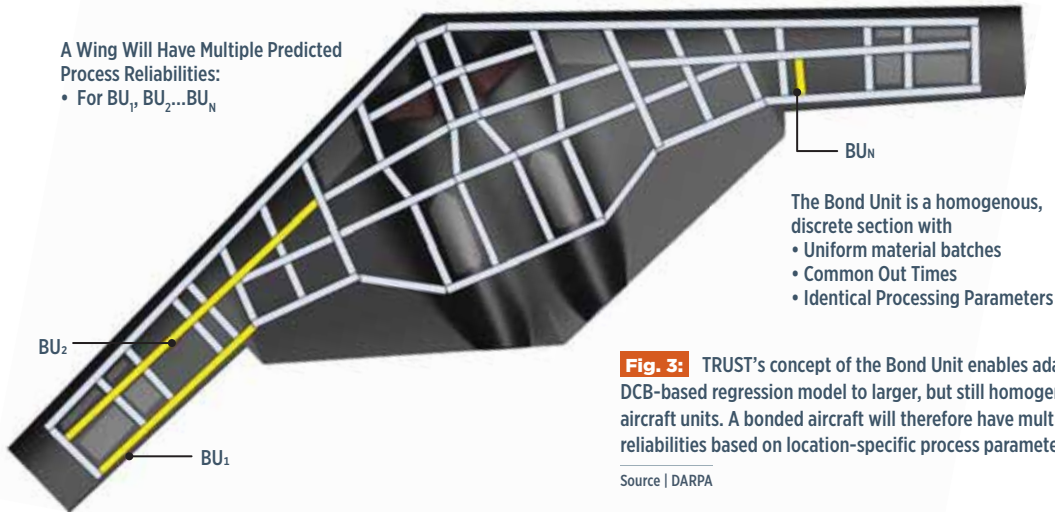


**Fig. 2:** The surfaces of each failed DCB coupon (in gray) were scanned and processed pixel by pixel to quantify, in the bottom image, the relative fraction of cohesive failure (green), laminate failure (blue) and interfacial failure (red) per the color-code. Source | DARPA

Researchers divided data collection into three rounds in order to build knowledge with each round rather than risk designing all the experiments poorly based on limited initial information. The first round was a small study of 15 panels to investigate five of the variables expected by Lockheed Martin materials and process (M&P) engineers to impact bond performance. These initial variables included surface-prep (SP, including, sandpaper grit, sanding duration), vacuum pressure during cure (V) and bond line contamination from hand lotion (L) and skin oil (SO). Test panels were built so that only one variable was modified at a time. In parallel, DOE I was developed, leveraging TRUST M&P engineers’ knowledge, to evaluate bond performance vs. four additional process variables: pre-bond temperature, (T) pre-bond humidity (H), adhesive outtime (OT) and the time between surface preparation and bonding (SB, generalized as sand-to-bond time, irrespective of whether sanding was employed). Interactions were also evaluated, such as surface-prep and adhesive outtime (SP:OT).

Testing was performed in two phases. The specimen was first “pre-cracked” by loading it at 1 mm/min until the crack extended 3-5 mm from the insert. The specimen was then unloaded. The second phase — the actual fracture-toughness test — then loaded the specimen at 5 mm/min until failure. The entire load-displacement history was recorded.

The goal for the third round of testing (DOE II) was to create a model to predict  $Mean G_R$  (the average fracture toughness over the first 76.2 mm of crack length in the DCB) as a function of the manufacturing process. Statistical tools and metrics then were used to select which of the manufacturing variables described above would be included in the final BPC model. One such tool is cross-validation. This uses separate data to build a model vs. assessing its accuracy in order to avoid selecting a model that includes too many terms and becomes less predictive as a result. Stepwise regression, which starts with a single term and then incorporates additional terms one at a time, also was used to make the process of exploring different combinations of variables in the model more tractable. The final set of variables, selected because they best predicted bond reliability, is shown in the lower left of Fig. 1 (p. 38), titled: Input Models. But how was the model’s ability to predict  $Mean G_R$  as a function of the manufacturing process evaluated? The DCB coupons provided that mechanism as well. »

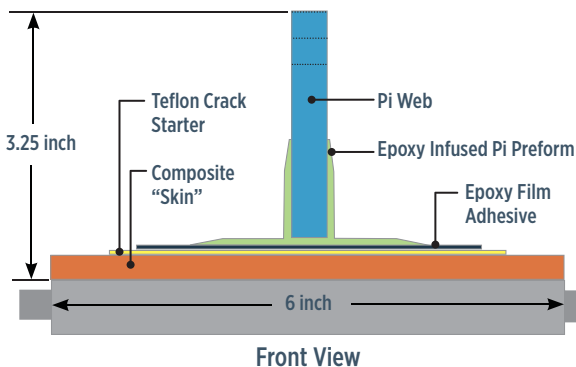


### Bond failure analysis

By modeling each adherend of the DCB coupon analytically as a beam on an elastic foundation, the TRUST team derived a  $G_{Ic}$  that is equivalent to the ASTM D 5528 method and also predicted the instantaneous crack length from the load-displacement history that matched with measured crack lengths. This modified method greatly improves testing efficiency and eliminates subjective manual crack length measurement during testing, thus enhancing the quality of the fracture toughness data. TRUST used this test to quantify the performance of the bond, which can fail in the laminate (laminate failure, LF), in the adhesive (cohesive failure, CF), in the adhesive-substrate interface (interfacial failure, IF) or via a combination. (Note: According to adhesive bonding science, CF is the preferred failure mode.) TRUST was able to develop a critical forensic process to determine overall bond quality by relating analysis of these failure modes to the overall fracture toughness measured in the DCB testing.

**Fig. 4:** The Pi-CB specimen is similar to a DCB in that an uncured adherend, in this case, an infused pi preform, is adhesively cobonded to a precured composite substrate, then tested in Mode I opening. This configuration characterizes the viability of the bond in an aircraft-realistic geometry.

Source | DARPA

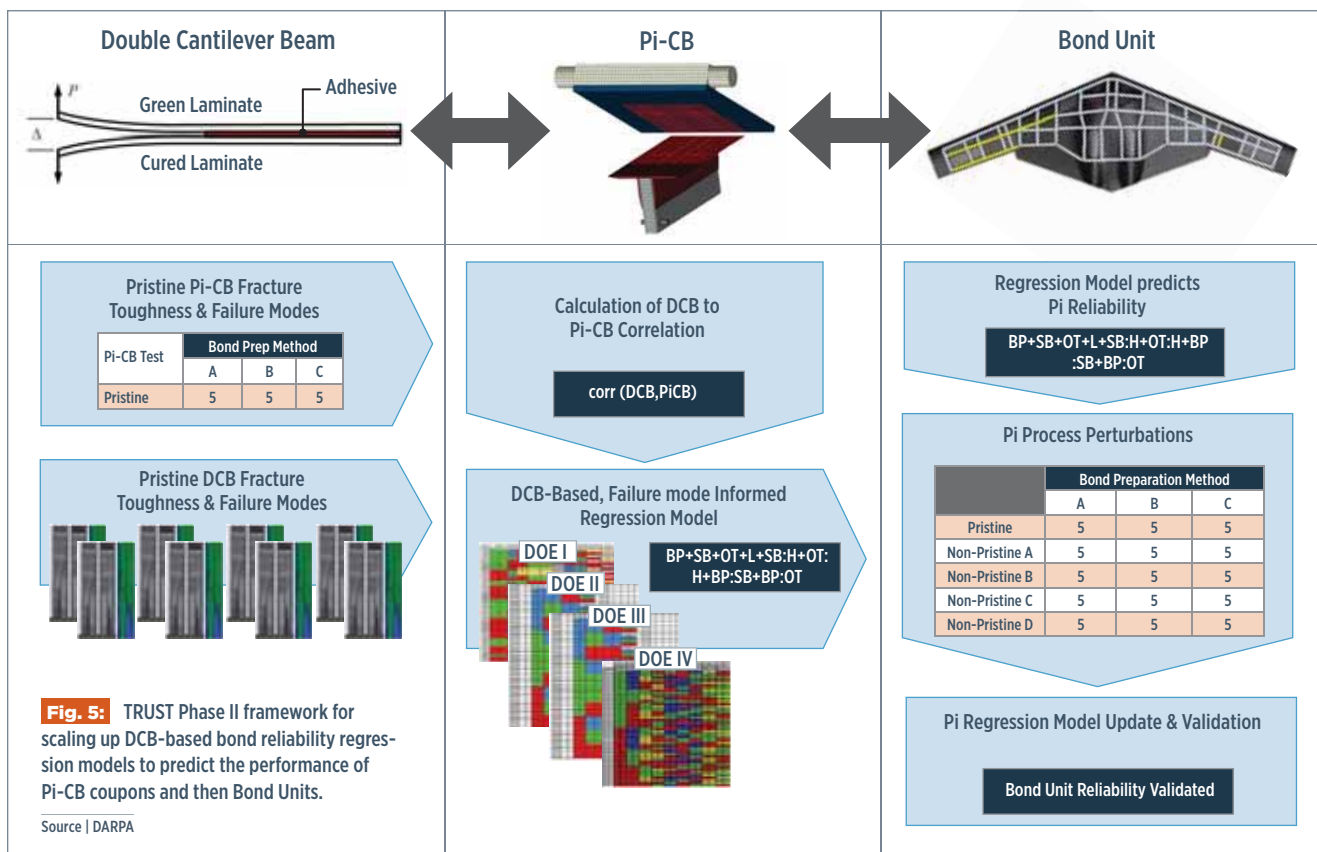


Following complete separation of the DCB coupon, photo images of the fracture surface of each DCB adherend were taken using a flatbed scanner (see Fig. 2, p. 39). Matching light gray regions indicated CF, matching dark regions pointed to LF, while IF was denoted by gray adhesive on one surface and dark laminate at the mating surface. SwRI developed an algorithm and image-processing software to determine the failure mode pixel by pixel and automatically calculate percentage of CF, IF, and LF per tested coupon. Visual inspection of multiple coupons has validated the accuracy of the SwRI tool. Because standards for bonded composite DCB testing had not previously been established, TRUST set  $\leq 6\%$  IF as acceptable for its purposes.

This testing also enabled a method for calculating  $Mean G_R$ , which reflects fracture toughness of the entire relevant bond area (i.e., the first 76.2 mm of crack length after precrack), instead of using  $G_{Ic}$ , which describes only a single point. By combining the above image analysis with mathematical modeling of each DCB adherend, additional fracture mechanics data for the entire process was extracted. R-curves that quantified the toughness behavior throughout the fracture process were then plotted. (R is a material's resistance to cracking, so a plot of R vs. crack extension is called a crack-resistance curve, or R-curve.) A rule of mixtures approach was then used to compare expected vs. actual fracture toughness along the coupon. Data that are essentially equivalent are not insightful, but data that differ convey which manufacturing variable causes the deviation and can be used to inform the model. Data that are worse than expected expose process parameters that need elimination. Data that are better than expected reveal parameters that need to be continued.

### Bond process informatics system

With the predictive model developed and verified, the next task was to implement a bonding process data-collection protocol for use on the manufacturing floor. To that end, SwRI developed the bond process informatics system (BPIS). This prototype tool collects data from the manufacturing process, organizes it for



evaluation, and applies the BPC predictive model to establish bond quality. The system enables automatic, in-process quantification of bond reliability.

To use the system, the workforce advances each part through the manufacturing process, manually entering required information into computer data-entry fields and, thus, documenting the part's manufacturing history from material procurement to laminate fabrication, bond surface preparation, bonding, and, finally, machining and testing. The typical workflow includes more than 1,000 steps with more than 700 points at which measurements must be entered. Each bonded structure would have its own workflow, capturing key process variables for each bonded joint, including its substrate and adhesive material type, surface preparation, cure parameters, etc.

The data are then used by the BPC model to generate a reliability prediction for each composite bonded part as it is being produced. Displayed in the upper right of the data collection screen, the reliability prediction provides up-to-date feedback regarding the bond toughness throughout the process. When a new data collection job is created, the prediction displayed is based on estimated prior distributions for the key model variables. As observed data are entered for these variables, the model updates the prediction based on the new information. The reliability prediction should become more accurate as the bonded part progresses through the manufacturing process. Meanwhile, new data entered will influence prior distributions, enabling more accurate predictions on future jobs.

This prototype system gathered manufacturing data for much of the TRUST Phase I DCB coupon production and has successfully demonstrated the ability to quantify bond reliability. Further efforts will focus on decreasing data-entry time and error by using automated data-collection tools, such as bar codes, RFID tracking and programmed measurement-collection devices. Enabling the system for use on mobile devices could increase the immediacy and, therefore, the accuracy of manually entered data.

The BPIS' large data repository and analysis capabilities should enable functions beyond the current reliability quantification. Hanson explains, "Bayesian process control analyzes failure so that if you're on a path to a bad part, it can suggest how to bring that part back into control." By recommending specific actions that will improve bond integrity, the BPIS will advance process control.

### Refined bond evaluation standard

Throughout TRUST Phase I, the standard for a good bond was fracture toughness greater than 0.105 MPa-cm. This was an acceptable approach for the first phase of the project because it allowed the BPC system to evaluate bond reliability based on a simple "meets/does not meet" criteria evaluation. Early in Phase II, this admittedly too simplistic approach was refined by giving BPC the ability to consider failure modes and their impact on fracture toughness — i.e., the failed adherend image analysis and relation to R curves. This enabled a failure mode-informed regression model (FIRM), which is critical, because it prevents the BPC from mislabeling bad bonds as good and good bonds as bad. For »

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example, if a DCB has a fracture toughness of 0.112 MPa-cm and a 35% interfacial failure (which is larger than the threshold of  $\leq 6\%$  IF), this should automatically be counted as a bad process and bad bond, regardless of the acceptable measured fracture toughness. Similarly, a DCB with a CF-dominated failure mode (which is preferred), but with a measured fracture toughness significantly less than the known adhesive fracture toughness, should be classified as a bad process and bad bond. The regression model, then, must be "smart" enough to recognize that a tested DCB coupon showing 100% cohesive failure and a fracture toughness 20% lower than expected, was probably affected by moisture exposure or some other unacceptable condition during processing. The SwRI-developed FIRM enables a holistic approach to evaluation of good vs. bad bond processes for more accurate predictions of bond quality. The new model will be employed as TRUST Phase II continues development of composite processing parameters in DOE III, and examines the effect of contamination in DOE IV as it scales up to bonded aircraft structures.

TRUST also will investigate new, more robust surface-preparation methods and update the BPC informatics system for, and automate its capture of, new data types. One example is the ability to detect environmental contamination by electronically collecting and comparing environmental histories for substrates and adhesives developed from workzone identifiers and barcode scans that stitch together time and temperature data for all of the constituent materials and processes.

As one of its new data types, the TRUST BPC system will begin in Phase II to account for effects of contamination on bonded structure by characterizing six shop environments at LM Aero Palmdale. Testing on a DOE IV grid using 100 DCB panels will examine the effect of contamination and also capture water contact

angle measurements from Brighton Technologies' (Cincinnati, OH, US) Surface Analyst. This tool and Agilent Technologies' (Santa Clara, CA, US) hand-held Fourier Transform Infrared (FTIR) device will be characterized as inline inspection technologies for specification-compliant composite faying surfaces (see "Learn More"). Building on this research, TRUST seeks to gain statistical confidence that detrimental contaminants can be detected in the bonded unit.

### Maturing process control for scalability

The ultimate objective of TRUST Phase II, however, is to validate the ability to quantify bonded assembly reliability. The upgraded BPIS is a key prerequisite, because it helps scale up bond process control by integrating automated data collection directly from sensors on the factory floor. This also helps to reduce testing needs when qualifying larger bonded assemblies. But there are many other issues. Because manufacturing processes and materials across an aircraft are not uniform, the TRUST team recognized that new concepts



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would be required to conduct spatial reliability predictions. Among Phase II's early accomplishments was a definition for the concept of a Bond Unit (BU). Critical for the scale-up of BPC to full-size aircraft structure, the BU enables TRUST to adapt the DCB-based regression model to predict the performance of large aircraft structures.

As shown in Fig. 3, p. 40, a wing comprises multiple individual BUs, each a homogeneous section of pi-joined structure (see "Learn More"). Homogeneity is defined by limiting variability in the parameters that are known to affect the quality of a bond, including material batches (i.e., one adhesive batch and one prepreg batch), a common out-time across the unit and processing parameters. When there is lack of homogeneity, by definition, the BU is split into two or more new BUs (BU<sub>1</sub>, BU<sub>2</sub>, etc.). Similar to the way the BPIS tracks differences between DCB panels and predicts the reliability of their bonds, this scaled-up BPC system will track differences between each BU and predict their reliability across the aircraft.

To demonstrate the scaled-up BPC system validity, LM Aero Palmdale developed the Pi-CB test (Fig. 4-5, p. 40-41). This uses a DCB-style test specimen but replaces one monolithic adherend with a pre-impregnated pi preform, mimicking actual aircraft structural joints. Because manufacturing parameters critical to bond performance will be held constant, the Pi-CB test coupon is a suitable surrogate for an actual BU, which will validate bond performance against predictions. TRUST will generate failure-mode-informed fracture toughness for pristine Pi-CBs as a measure of bond quality and combine this data with that from pristine DCB coupons. These data sets will enable calculation of a DCB-to-Pi-CB correlation factor, which is the first step to predict BU reliability with DCB data. Combining the correlation factor with the DCB-based FIRM will enable the generation of a regression model for pi joint reliability. This regression model will be built upon by testing another set of Pi-CB coupons whose pi-specific process parameters (e.g., pi resin content) are varied. These test data will further inform the pi regression

model, at which point the model will be used to predict and validate BU performance.

TRUST has made huge progress in tackling the uncertainty that has plagued bonded composite structures for decades. "Once we have process control for the whole bonded structure in hand and vetted, I expect the TRUST framework to be standard practice for bonded structures in the future," says Maher. "This could really be a game-changer for aircraft manufacturing." **CW**



#### ABOUT THE AUTHOR

CW senior editor Ginger Gardiner has an engineering/materials background and has accrued more than 20 years in the composites industry.  
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# RAILS TO TRAILS

## Composite deck converts old railroad span to pedestrian trail crossing

► The Rails-To-Trails Conservancy (Washington, DC, US) was formed in 1983 to re-purpose unused rail corridors nationwide in support of a growing network of recreational walking and biking trails. Broad Top Township in Bedford County, located between Pittsburgh and Harrisburg in southern Pennsylvania, participates in Rails-To-Trails through a local nonprofit organization. That group wanted to convert an abandoned HB&T railroad grade to a pedestrian- and bicycle-friendly trail that would connect two existing public parks, but was faced with having to do the same to an existing 108m railroad trestle bridge spanning a river that separated the parks.



The Rails-To-Trails Conservancy sought help from Composite Advantage (Dayton, OH, US) to add a composite bridge deck to this abandoned railroad trestle bridge, to complete a pedestrian/ bike trail in southern Pennsylvania.

Source | Composite Advantage



Because the trestle bridge structure had exposed rivet heads where the bridge deck would normally be seated, it was not possible to use a conventional flat sandwich panel for the deck. Instead, “steps” were molded into the deck panel undersides to align with flat areas between rows of rivet heads on the main trestle girders (panels in inset photo are shown bottomsides up, to expose the “steps”).

Source | Composite Advantage



The finished deck, with railings, was installed in only three days.

Source | Composite Advantage

The nonprofit chose to work with **Composite Advantage** (CA, Dayton, OH, US), for a new, FiberSPAN fiber-reinforced polymer (FRP) composite bridge deck. The deck needed to fit atop the old iron truss support structure. Although the latter was still structurally adequate, its two upper girders, on which the deck would sit, were spaced 3m on center, a wide spacing for a pedestrian bridge, says CA president Scott Reeve: “The wider the support spacing, the greater the deck depth had to be to meet deflection criteria under load of  $L/500$ .” (Maximum deflection equals spacing length divided by 500.) Further, says Reeve, “Unlike conventional bridge decks, old structures like the HB&T trestle bridge used girder flanges with rivet heads on top” (see second photo). That prevented the use of a simple flat panel.

Given the distance between the girders and the exposed rivet heads, CA molded 15 4m-wide by 125-mm-deep sandwich-design deck panels, with upper and lower skins of fiberglass. To ensure they would seat properly on the girders, says Reeve, “the FRP deck panels were molded with integral spacers or steps on the underside to ensure the deck would clear the rivet heads.” (Steps shown in photo at left were made to seat on the flat area between the rows of rivets on each large girder in the photo above.) Lastly, molded-in steel box tubing on the outer edges provided a high-strength load path for support when railing posts were attached.

A Broad Top Township crew bolted down the FRP deck panels to threaded shear studs welded to the tops of the girders. The FRP deck panels took just three days to install and the HB&T bridge and trail opened to the public in November 2014. **CW**

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» Wooden pallets have dominated shipping since the early 20<sup>th</sup> Century, but their tendency to splinter, warp and absorb moisture (leading to contamination) has left the door open to alternatives. Unreinforced plastic pallets reportedly lack strength and their performance suffers in both hot and cold temperatures. That's why RM2 (Luxembourg and Chatham, NJ, US) spent US\$10 million over 10 years to develop BLOCKPal pallets, made from glass fiber-reinforced

polyurethane pultrusions. BLOCKPal pallets reportedly feature high impact resistance, a high strength-to-weight ratio and minimal creep, and perform well from -20°C to 80°C. Further, they meet ISO 8611 standards, use US Federal Drug Admin. (FDA, Washington, DC, US)-compliant materials and have passed the UL 2335 "Fire Test of Storage Pallets" without the use

of controversial chemical fire retardants. RM2 estimates that BLOCKPal pallets are up to 20 times more durable than wooden pallets. During independent tests at the Virginia Tech Center for Packaging and Unit Load Design (Blacksburg, VA, US), the BLOCKPal pallet achieved a pooled pallet rating of 1,633 kg, with a safety factor of 2. As a result, RM2 not only sells BLOCKPal pallets, but also rents them *and* offers radio frequency identification (RFID) tracking: What was once a one- or two-trip consumable is now a real asset.

BLOCKPal pultrusions are made using Baydur PUL 2500 two-part polyurethane resin from **Bayer MaterialScience LLC** (Pittsburgh, PA, US). Bayer also provided pultrusion tooling, part design recommendations, material enhancements and support.

RM2 pultrudes three basic profiles: feet, slats and channels. It paints the feet a distinctive yellow, applies an anti-skid coating and assembles the pultrusions into four standard pallet sizes as well as bespoke sizes for specialized applications. **cw**

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## ELECTRIC FERRY RUNS QUIETLY WITH COMPOSITES

**Infused sandwich construction hull and superstructure panels offset battery system weight**



Source | DIAB

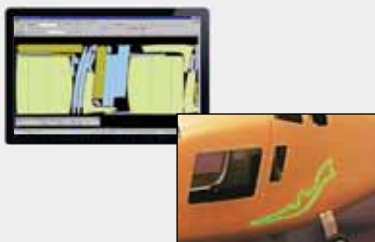
► For marine transportation operators driven by ever-tighter environmental regulations, emissions and nuisance noise reduction have joined increasing efficiency as top priorities. One means for meeting them all is electric propulsion. A case in point is Stockholm, Sweden's SL public transportation system and its ferry operator Ballerina, which recently introduced its first battery-powered ferry boat. Featuring a high-tech marine lithium-ion (Li-ion) battery system from Saft Group (Paris, France) the *M/S Sjövägen* makes 10 stops on a 50-minute route through the Stockholm waterways all year, completing eight round trips per day. Designed and manufactured by boatbuilder Faaborg Værft (Faaborg, Denmark) with engineering firm Principia North A/S (Svendborg, Denmark) and marine fire-suppression

expert Wilhelmsen Technical Solutions (Lysaker, Norway), the ferry's composites were a must for the majority of the vessel, to offset the weight of the battery packs.

The ferry's hull and superstructure feature fiberglass-faced sandwich construction cored with Divinycell H polyurethane/polyvinyl chloride foam, a high-strength closed-cell product with good fatigue resistance and low water uptake, made by **DIAB International AB** (Laholm, Sweden). "We used the sandwich composite panels mainly for the hull, topsides and wheelhouse," says Jan Ulrich Mortensen, managing director at Faaborg Værft. Christian Karlsson, DIAB's sales/marketing manager for Europe and Asia, says the hull sandwich was layed up in a one-piece mold and infused. The superstructure components were assembled from infused flat panels. "It is a great solution," sums up Mortensen, "due to its strength, noise reduction and vibration-damping properties." **CW**

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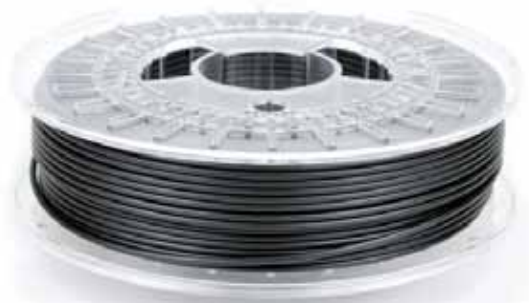
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**3A Composites** (Sins, Switzerland) has introduced AIREXT10, the first foam core derivative based on the new technology AIREX GEN2, a highly industrialized production process introduced by 3A Composites last year. AIREXT10 features what is said to be a homogenous cell structure and highly enhanced mechanical characteristics when compared to 3A's AIREX T92. The company says its new direct extrusion process allows for consistent material properties and good quality control. The material is targeted toward applications such as marine and wind energy, as well as nascent markets with large potential for sandwich technologies, such as the automotive industry. [www.corematerials.3acomposites.com](http://www.corematerials.3acomposites.com)



### » ADDITIVE MANUFACTURING

#### Carbon fiber-reinforced filament for 3D printing

**ColorFabb** (Venlo, The Netherlands) has introduced XT-CF20, an additive manufacturing filament based on the Amphora 3D copolyester (from Eastman Chemical Co., Kingsport, TN, US) reinforced with carbon fiber at loadings of up to 20%. The filament, denoted XT-CF20, prints with a matte finish, offers a flex modulus of 6.2 GPa, a strain at break of 8-10%, a  $T_g$  of 80°C, and offers high melt strength, high melt viscosity, low odor, compatibility with several 3D printing platforms and diameters of 1.75 mm or 2.85 mm. ColorFabb notes that carbon fiber's abrasiveness requires the use of stainless steel or hardened copper alloy nozzles on printing heads.

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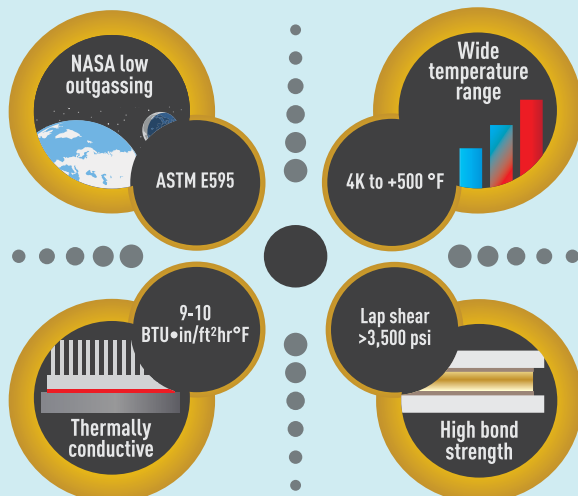
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## » METROLOGY

**Portable coordinate measuring machine**

**Hexagon Metrology** (North Kingstown, RI, US) reports that its 4.5.4 SF coordinate measuring machine (CMM) has been updated to expand capabilities. This shop-floor CMM now includes integrated workspace LED lighting to assist the operator in poor lighting conditions. In addition, the bolt-hole pattern in the CMM's granite base has been revised to accommodate a 300-mm kinematic plate for repeatable dedicated fixturing. Among other improvements are granite etching to define the measurement envelope in the x and y axes, optional programmable status lighting on the z-axis that signals the machine's progress in the measurement routine, power switches located on the front of the machine to add ease-of-use, and an integrated monitor and keyboard arm. The 4.5.4 SF CMM can fit through a standard size door and can be located anywhere dimensional inspection is needed. The 4.5.4 SF also uses standard 110/220V outlets with no need for shop air. Other features, such as advanced thermal isolation, temperature compensation and covered bearing ways, help enhance the unit's durability.

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## » BONDING TECHNOLOGY

**Two-component epoxy for aerospace applications**

**Master Bond** (Hackensack, NJ, US) reports that it has developed a two-part epoxy system for aerospace applications, called EP90FR-V. It has passed the vertical burn test portion of the *Federal Aviation Register (FAR)* standard 14 CFR 25.853(a) for flame retardancy. Master Bond says this enables it to be used in aerospace interior panels, door-frame linings and floor/door assemblies. EP90FR-V has a 1:1 mix ratio by weight and viscosity of 20,000-40,000 cps. This system is suitable for bonding, sealing, coating, potting and encapsulation applications. It is said to bond well to composites, metals, glass, ceramic and many plastics. EP90FR-V, which is nonhalogenated, is serviceable at temperatures from -51°C to 121°C. This system is color-coded, which facilitates mixing; the color of Part A is black, Part B is white and the cured material is gray. It can be packaged in guns, FlexiPaks and premixed and frozen syringes. It is also available in standard packaging kits.

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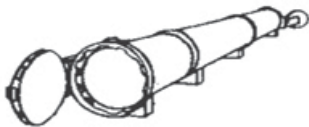


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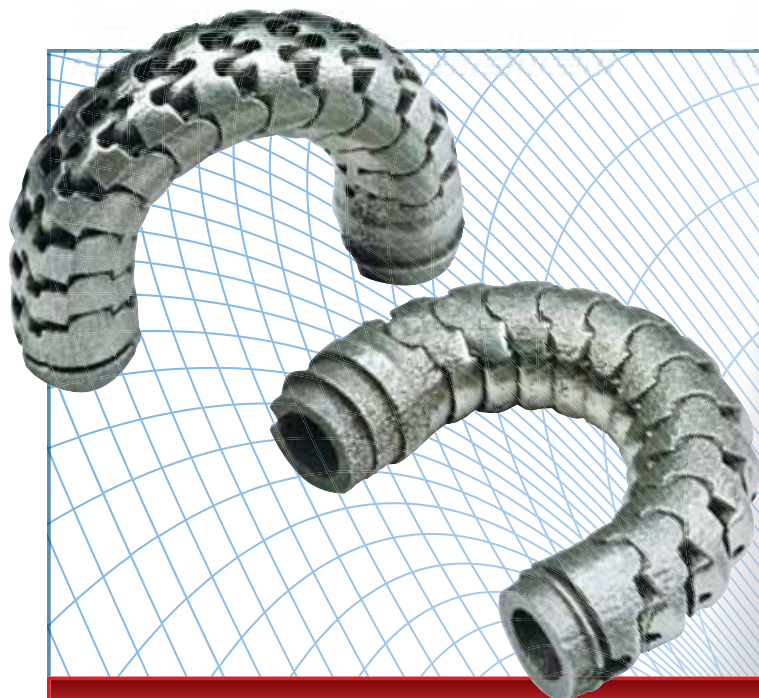
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# The building envelope: FRP unitized façades

New composite design reduces framing, simplifies construction and improves performance vs. conventional aluminum-framed glass curtainwalls.

By Ginger Gardiner / Senior Editor

» Unitized panel systems have become a popular alternative to conventional, stick-built construction in building envelopes. Prefabricated offsite, under controlled factory conditions, these systems vastly simplify onsite installation, decreasing expensive jobsite labor and shortening construction schedules. In 2009, the International Code Council's (ICC, Washington, D.C.) *International Building Code (IBC)* approved the use of fiber-reinforced polymer (FRP) composites in unitized panels. But it was only recently that Kreysler & Associates' (American Canyon, CA, US) Fireshield 285 panel system, an FRP system that passes the NFPA 285 fire-resistance certification, has allowed economical use on buildings taller than 12m. That system currently forms the largest FRP façade installation in the US, on the San Francisco Museum of Modern Art (SFMOMA) expansion (see "Learn More"). Fireshield 285 offered SFMOMA the least expensive solution — reportedly 20% less than competing materials — and eliminated more than 450,000 kg of secondary steel structure. But Kreysler's FRP panels still required the use of a secondary aluminum panel framing system manufactured by renowned façade design/build company Enclos (Eagan, MN, US).

In the wake of the SFMOMA project, Kreysler, Enclos and architects Gensler Los Angeles (Los Angeles, CA, US) tasked design teams in a digital fabrication course at the Material Innovation Lab

within California Polytechnic State University – San Luis Obispo's (Cal Poly SLO, CA, US) Dept. of Architecture with developing unitized panel systems that not only exploit the benefits of FRP to integrate unique molded-shape aesthetics with thermal insulation, but *also* carry more of the substructural load.

## Improved efficiency, reduced layers

"Because composites can handle structural loads, we can get rid of the aluminum structure standard in today's unitized panel systems," explains Cal Poly SLO's Prof. Mark Cabrinha. That's a plus, especially with windows. Cabrinha explains, "In a house, windows in a wall are placed in what we call punched openings. In an office building, however, a continuous wall of windows hangs *in front* of the steel structure, and thus, is called a curtainwall."

Curtainwalls are typically thin and made from aluminum frames called mullions, which support glass, metal and/or thin stone panels. Aluminum-framed curtainwalls are coming under fire, today, because aluminum, although lightweight, is highly conductive. It radiates summer heat *into* air-conditioned interiors and *out* of heated interior spaces in cold weather, significantly increasing energy costs. Further, aluminum itself is produced in an energy-intensive process, and that affects a building's overall LEED rating, a voluntary third-party certification that evaluates a building's construction and operational sustainability (see "Learn More"). "Now we start talking about significant improvement in thermal performance and CO<sub>2</sub> footprint because aluminum is a very energy-intensive material to produce," says Cabrinha.

The design teams used a combination of parametric design software, hands-on prototyping and digital fabrication processes to iteratively develop multiple FRP unitized façade concepts (see Fig. 1, p. 56). Of these, one named RELAXED

offered the most near-term commercial potential. A practical solution that could meet today's large demand for retrofitting aging buildings where higher performance is required without increasing dead loads, "RELAXED achieves a water-tight enclosure and primary exterior surface in the same prefabricated element," explains Cabrinha. "The design also integrates thermal insulation and drastically cuts solar gain vs. the all-glass façades commonly used today."

Cabrinha also sees that RELAXED opens an expanse of new design



## As different as day and night

Tasked with rethinking conventional curtainwall design, the Cal Poly San Luis Obispo Material Innovation Lab's student design team developed the RELAXED concept with windows mounted perpendicular to the wall plane, to avoid heavy daytime solar exposure and provide attractive exterior lumination after dark.

Source | Cal Poly SLO