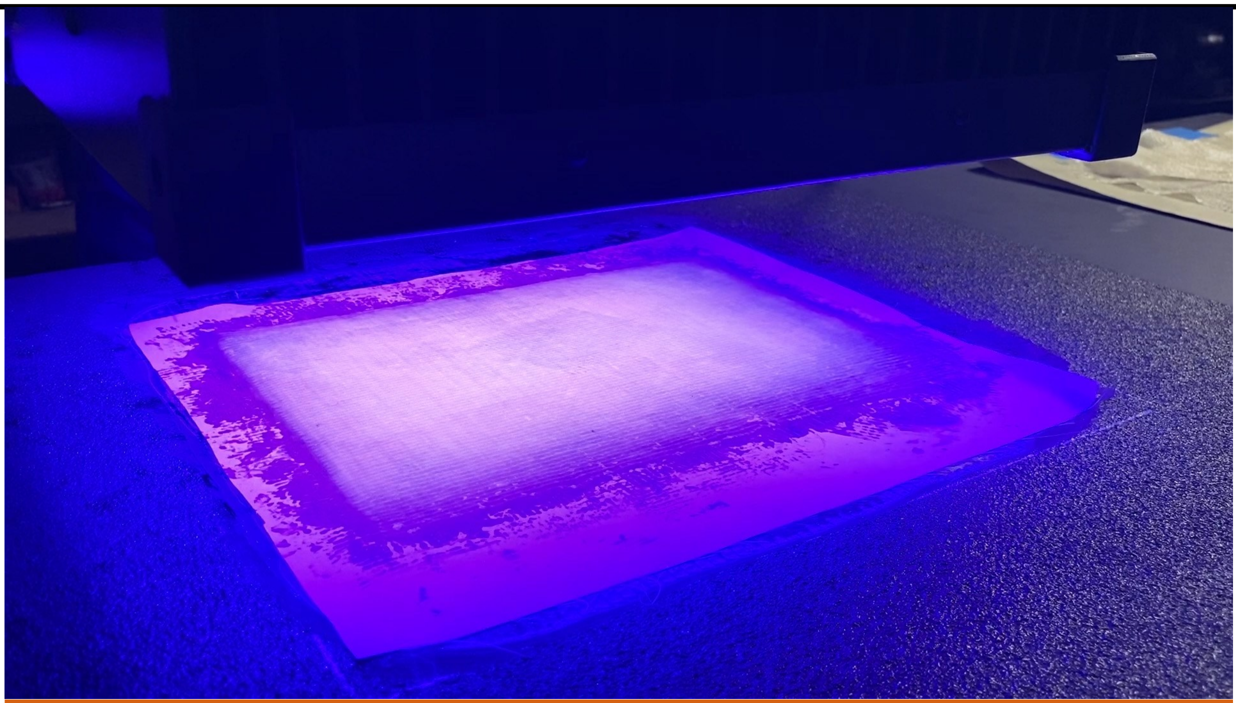


New technology for in-field repair of composite structures

Portable kit enables patch repairs using UV-cure glass/vinyl ester or room-temp stored carbon/epoxy prepregs and battery-powered curing equipment.

Modular deployable bridges are a key asset in military tactical operations and logistics, as well as for restoring transportation infrastructure during natural disasters. Composite construction is being investigated to reduce the weight of such bridges, which in turn reduces the burden on transport vehicles and launch-retrieval mechanisms. Composites also offer the potential for increase load-carrying capability and a longer service life compared to metal bridges. The Advanced Modular Composite Bridge (AMCB) was designed and built using carbon fiber-reinforced epoxy laminates (Fig. 1) by Seemann Composites LLC (Gulfport, Miss., U.S.) and Materials Sciences LLC (Horsham, Penn., U.S.). However, the ability to repair such structures in the field has been an issue hindering the adoption of composites.

In 2016, Custom Technologies, LLC (Millersville, Md., U.S.) was awarded a Small Business Innovation Research (SBIR) Phase I grant funded by the U.S. Army to develop a repair method that can be performed successfully by soldiers in the field. Based on this method, a Phase II SBIR grant was awarded in 2018 to demonstrate new materials and battery-operated equipment that could restore 90% or more of the structure's original strength, even when the patch repair is performed by a novice with no prior training. The feasibility of the technology was established by performing a series of analytical, material selection, test specimen fabrication and mechanical testing tasks, as well as small- and full-scale repairs.

From cracked ship decks to bridge decks

The principal investigator for both SBIR phases was Michael Bergen, founder and president of Custom Technologies, LLC. Bergen retired from Naval Surface Warfare Center (NSWC) Carderock with a 27-year tenure in the Structures and Materials Department, where he managed development and application of composite technologies for the U.S. Navy fleet. Also key to this project, Dr. Roger Crane joined Custom Technolo-

UV-cured prepreg patch repair

Even though the carbon fiber/epoxy prepreg repair that Custom Technologies LLC developed for in-field composite bridges was demonstrated to be simple and quick, a more expedient system was developed using glass fiber-reinforced UV-cure vinyl ester resin prepreg.

Photo Credit | Custom Technologies LLC

gies in 2015 after retiring from the U.S. Navy in 2012 with 32 years of service. His composites expertise includes technical publications and patents covering topics such as new composite materials, prototype manufacturing, joining methods, multifunctional composites, structural health monitoring and composite repair.

These two experts had already developed a unique process which used composites to repair cracking in 5456 aluminum superstructures on the USS Ticonderoga CG-47 class guided-missile cruiser. "The process was developed to reduce crack growth and serve as an affordable alternative to a $2-4 million deck plate replacement," says Bergen. "Thus, we had demonstrated that we knew how to do repairs outside of the lab and in a real service environment. But the challenge was that current methods for military assets are not very successful. The options are bonded doubler repair or remove the asset from service for depot level (D-level) repairs. There are so many assets sitting off to the side because a D-level repair is required."

What is needed, he continues, is a method that can be executed by a soldier with no experience in composites, using only a kit and repair manual. "Our goal was to make the process easy: read the manual, assess the damage and do the repair. We didn't want any mixing of liquid resins because that requires precise measuring to ensure full cure. We also needed a system with no HAZMAT waste to handle after the repair is completed. And it had to be packaged as kits that can be deployed by the networks already in place."

FIG. 1 **Composite bridges, key in-field assets**

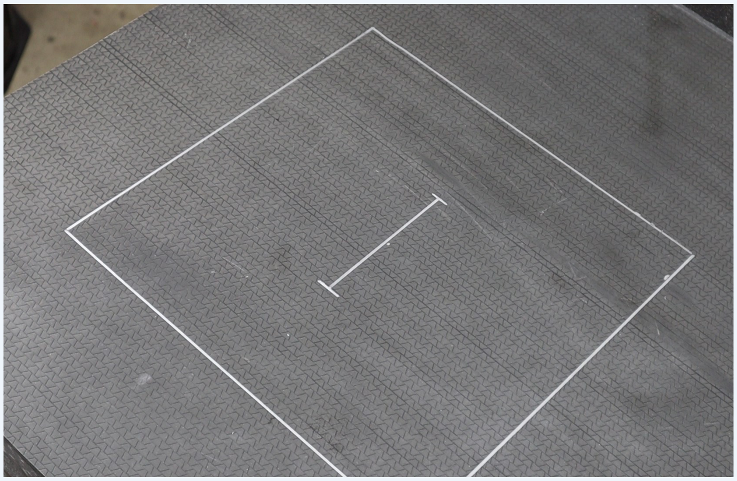
The Advanced Modular Composite Bridge (AMCB) was designed and built by Seemann Composites LLC and Materials Sciences LLC using carbon fiber-reinforced epoxy composites. Photo Credit: Seeman Composites LLC *(left)* and U.S. Army *(right)*.

Novel bonded patch materials

One solution that Custom Technologies has successfully demonstrated is a portable kit that enables a bonded composite patch, tailored to the size of the damage, up to 12 square inches, using a toughened epoxy adhesive. Demonstrations were completed on composites representative of the 3-inch-thick AMCB deck, which features a 3.0-inch-thick balsa core (15 pounds per cubic foot density) with faceskins comprising two plies of Vectorply C-LT 1100 carbon 0°/90° biaxial stitched fabric, 1 ply of C-TLX 1900 carbon fiber 0°/+45°/-45° triaxial and 2 more plies of C-LT 1100 for 5 plies total. "We decided the kit would use premade patches in a quasi-isotropic layup of similar multiaxials so that fabric orientation wouldn't be an issue," says Crane.

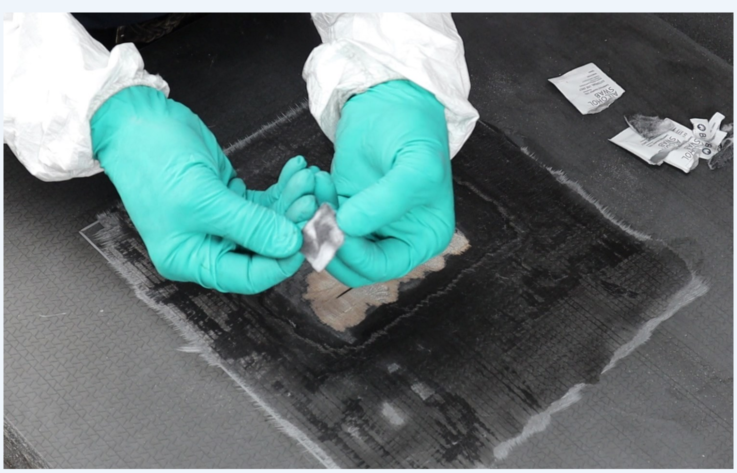
The next issue was the resin matrix for laminating repairs. To avoid mixing liquid resins, the patch would use prepregs. "However, the challenge for these is storage," explains Bergen. So Custom Technologies teamed with Sunrez (El Cajon, Calif., U.S.) to trial a glass fiber/vinyl ester prepreg that cures in 6 minutes using ultraviolet (UV) light. It also worked with Gougeon Brothers (Bay City, Mich., U.S.), which suggested a flexible epoxy resin film. Early investigations had demonstrated that epoxy was the most suitable for carbon fiber prepreg. The final material demonstrated cures in 1 hour at 210°F/99°C with a long shelf life at room temperature. No low-temperature storage is required. The resin will also cure at higher temperatures, for example 350°F/177°C if a higher glass transition temperature (Tg) is required. Both prepregs are supplied in the portable repair kit as premade prepreg patch layups sealed in plastic film envelopes.

Because repair kits may be in storage for extended time periods, Custom Technologies was required to perform a shelf-life study. "We bought four hard plastic cases — typical of the type the military uses for shipping equipment — and put samples of the epoxy adhesives and vinyl ester prepreg in each one," says Bergen. The cases were then placed in four different locations for testing: on the roof of Gougeon Brothers' facility in Michigan, on the roof of an airport in Maryland, outdoors at a facility in Yucca Valley (California desert) and at an outdoor corrosion testing lab in southern Florida. All of the cases had data loggers, Bergen notes, "and we'd pull data and material samples every three months for evalutaion. A maximum temperature of 140°F was recorded by the boxes in Florida and California, which is a real challenge for most repair resins." In addition, Gougeon Brothers has tested the newly developed neat epoxy resin in-house. "Samples held for months in an oven at 120°F started to polymerize," says Bergen. "However, for corresponding samples held at 110°F, the resin chemistry advanced only a small amount."

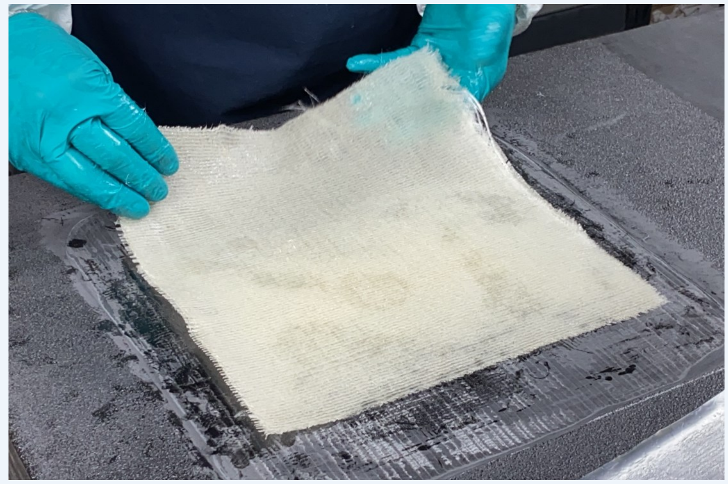


1 This test panel shows the 3-inch hole diameter to simulate damage marked at center as well as the repair perimeter.

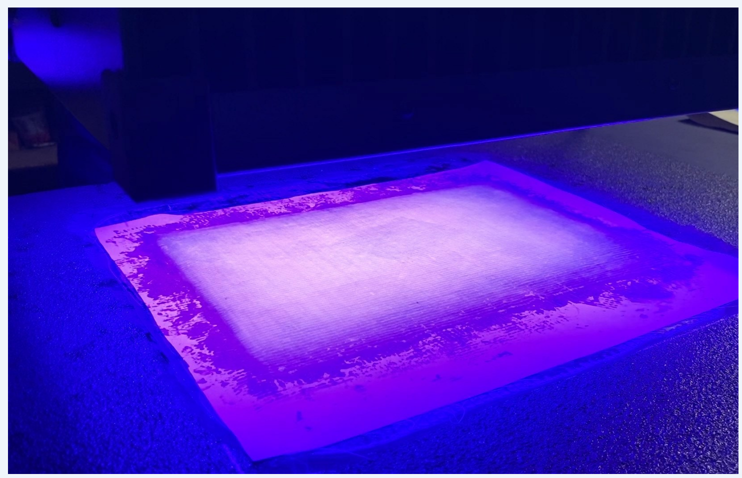
2 A battery-powered hand grinder is used to remove damaged material and scarf a 12:1 taper to receive the repair patch.



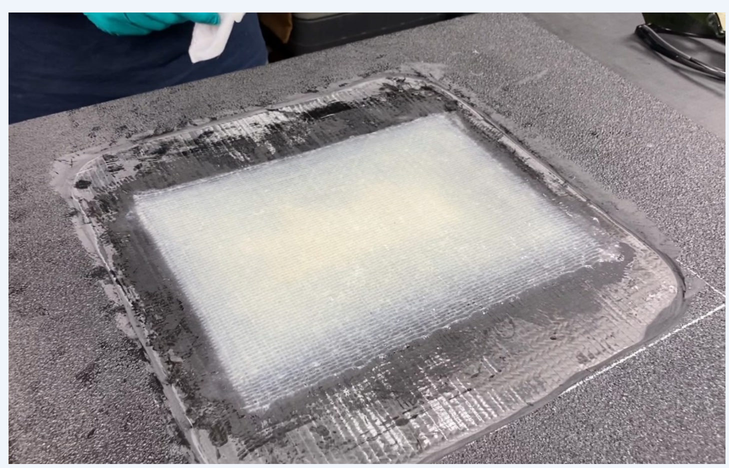
3 The prepared repair area is then cleaned with a solvent wipe using disposable alcohol pads.



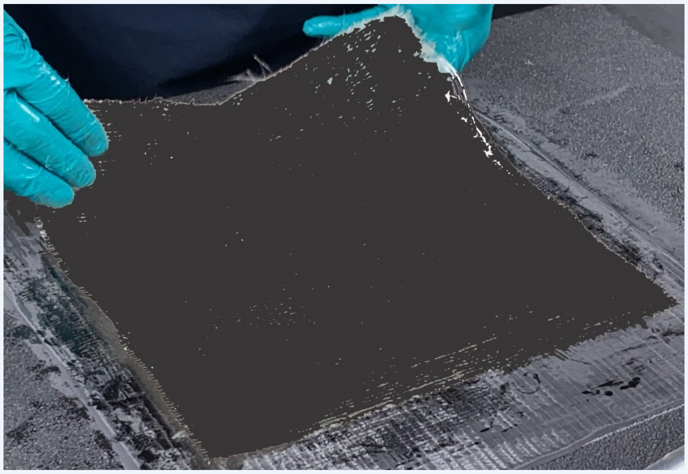
4 The glass fiber/vinyl ester repair patch is cut to size and positioned on the repair area.



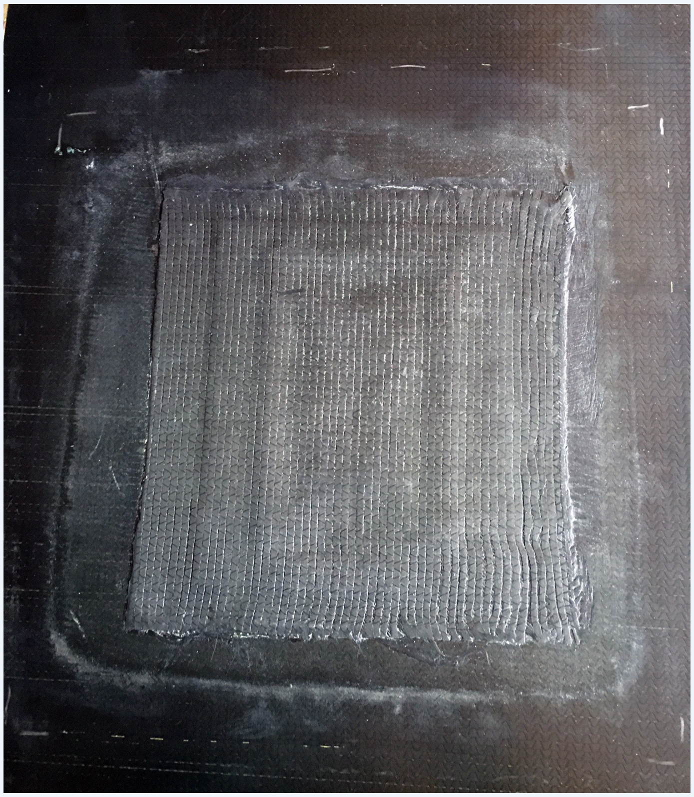
5 After a peel ply is placed over the repair area, the patch repair is cured using a cordless UV light for six minutes.



6 The finished repair.



7 For the carbon fiber/epoxy prepreg, the repair area was vacuum bagged and cured using a battery-operated hot bonder for 1 hour at 210°F/99°C.



8 Repairs for both patch materials showed > 75% strength restoration on 4-inch-wide beams and >90% strength restoration on larger test panels and the AMCB model.

Repair testing

In order to demonstrate the repair technology, representative laminates had to be manufactured, damaged and then repaired. "In both the Phase I and II projects, we initially worked with small-scale, 4-inch by 48-inch beams and 4-point bending tests to assess the viability of our repair process," says Crane. "We then transitioned to 12-inch by 48-inch panels, applying load to create a biaxial stress state to failure to evaluate the repair performance. We also completed repairs to a model we had built of the AMCB in the Phase II project (Fig. 2)."

The test panels used to demonstrate the repair performance were fabricated using the same pedigree in laminate and core as the AMCB built by Seemann Composites, but we scaled down the facesheet thickness from .375 inch to 0.175 inch, based on the parallel axes theorem," says Bergen. "This we calculated using the finite element analysis we had developed with XCraft, Inc., (Boston, MA U.S.) for the repair design."

"We wanted to simulate a higher degree of damage in the test panels than what they're likely to see on in-field bridge decks," says Bergen. "So, our approach was to use a hole saw to make a 3-inch-diameter hole. We then pulled the plug of damaged material out and performed an 11:1 scarf using a handheld pneumatic grinder." Carbon fiber fabrics used to produce the carbon fiber/epoxy prepreg were purchased from Vectorply Corporation (Phenix City, Ala., U.S.) and balsa core used to prepare the test materials and model were purchased from Core Composites (Bristol, R.I., U.S.).

For the carbon/epoxy repair, explains Crane, once the "damaged" facesheet material was removed and the appropriate scarf applied, the prepreg was cut to width and length to match the taper of the damage area. "For our test panels, this required four plies of prepreg that brought the repair material to be even with the top of the original undamaged carbon facesheet. After this, three overplies of the carbon/epoxy prepreg were centered over this repair section. Each successive ply extended 1 inch on all sides of the ply below, which provided a gradual load transfer from the "good" surrounding material into the repaired area." The total time to perform this repair — including repair area preparation, cutting and placing the repair material, and applying the cure procedure — was approximately 2.5 hours.

Even though the carbon/epoxy repair is simple and quick, the team recognized the need for an even more expedient solution that could restore performance. This led to exploring an ultraviolet (UV) cured prepreg supplied by Sunrez Corporation (El Cajon, Calif., U.S). "Interest in Sunrez vinyl ester resin was based on previous navy experience with Mark Livesay at Sunrez," Bergen explains. "We began by providing Sunrez with a quasi-isotropic glass fabric to prepreg and evaluate the cure profile under varied conditions. Further, knowing that vinyl ester resin

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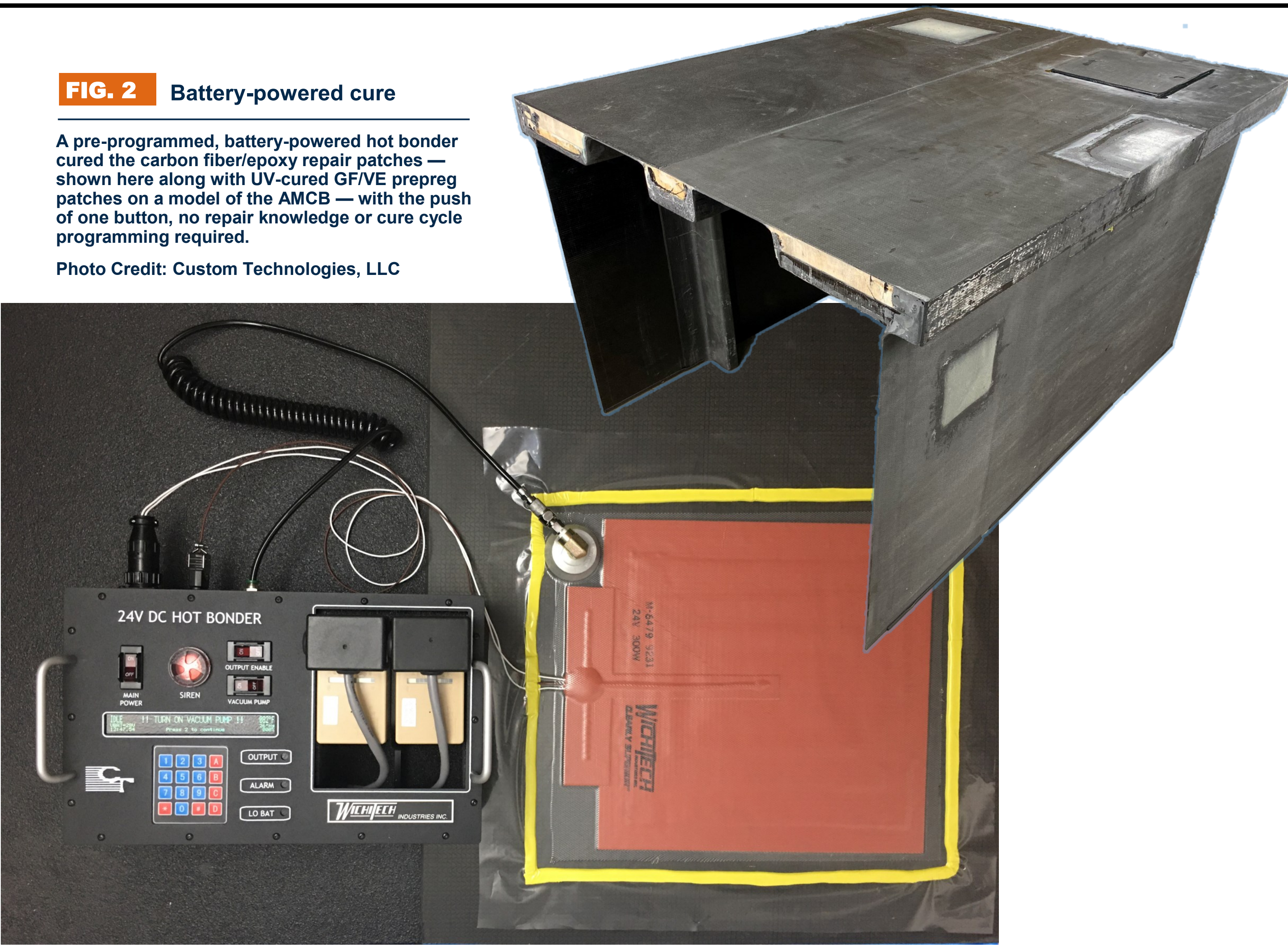
FIG. 2 **Battery-powered cure**

A pre-programmed, battery-powered hot bonder cured the carbon fiber/epoxy repair patches — shown here along with UV-cured GF/VE prepreg patches on a model of the AMCB — with the push of one button, no repair knowledge or cure cycle programming required.

Photo Credit: Custom Technologies, LLC



does not provide as suitable secondary bonding properties as epoxy does, there was an additional effort to evaluate various bondline coupling agents and qualify one for this application."

Another issue was that glass fiber does not provide the same mechanical properties as carbon fiber. "This was addressed by using one additional ply of the glass/vinyl ester compared to the carbon/epoxy patch," says Crane. "The reason only a single additional layer was required was that the glass material was a heavier fabric." This resulted in a suitable patch that could be applied and then cured in 6 minutes even in very cold/freezing infield temperatures with no need to provide heat. Crane notes this repair could be completed in 1 hour.

Both patch systems were demonstrated and tested. For each repair, the damaged area is defined (step 1) and removed using a battery-powered hand grinder (step 2). The repair area is then scarfed to a 12:1 taper. The scarfed surface was cleaned with alcohol pads (step 3). Next, the repair patch was cut to size, positioned on the cleaned surface (step 4) and consolidated with a roller to remove air bubbles. For the glass fiber/UV-cure vinyl ester prepreg, a peel ply was then placed over the repair area and the patch was cured using a cordless UV light for six minutes (step 5). For the carbon fiber/epoxy prepreg, the repair area was vacuum bagged and cured using a pre-programmed, one-button, battery-operated hot bonder for 1 hour at 210°F/99°C.

"We then performed tests to evaluate the adhesive bond of the patch and ability to restore the structure's load-carrying capability," says Bergen. Both systems showed > 75% strength restoration on the 4-inch-wide beams in the Phase I project and >90% strength restoration on larger test panels and the AMCB model in the Phase II project.

Novice success, future applications

One key aspect of the project was to prove that a novice could easily complete the repair. To do this, Bergen had an idea. "I had promised a demonstration to our two technical points of contact at the Army: Dr. Bernard Sia and Ashley Genna. At final review for the Phase I project, I asked Ashley, who had no prior repair experience, to perform the repair. Using the kits and manual we provided, she applied the patch and completed the repair without any issues."

Another key development is the battery-powered curing system (Fig. 3). "With in-field repair, you only have battery power," notes Bergen. "All of the process equipment jn our developed repair kit is cordless." This includes the battery-powered hot bonder that Custom Technologies developed with hot bonder supplier WichiTech Industries, Inc. (Randallstown, Md., U.S.). "This battery-powered heat bonder is pre-programmed to complete the cure, so the novice doesn't need to program for the cure cycle," says Crane. "They simply push the button, and it completes the appropriate ramp and soak." Regarding long-term charge capability, the batteries currently used last one year before they need to be recharged.

With the Phase II project now completed, Custom Technologies is preparing a follow-on enhancement proposal and collecting letters of interest and support. "Our goal is to mature this technology to TRL 8 and get it out into the field," says Bergen. "We also see potential for non-military applications."

ABOUT THE AUTHOR

CW senior editor Ginger Gardiner has an engineering/materials background and more than 20 years of experience in the composites industry.

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