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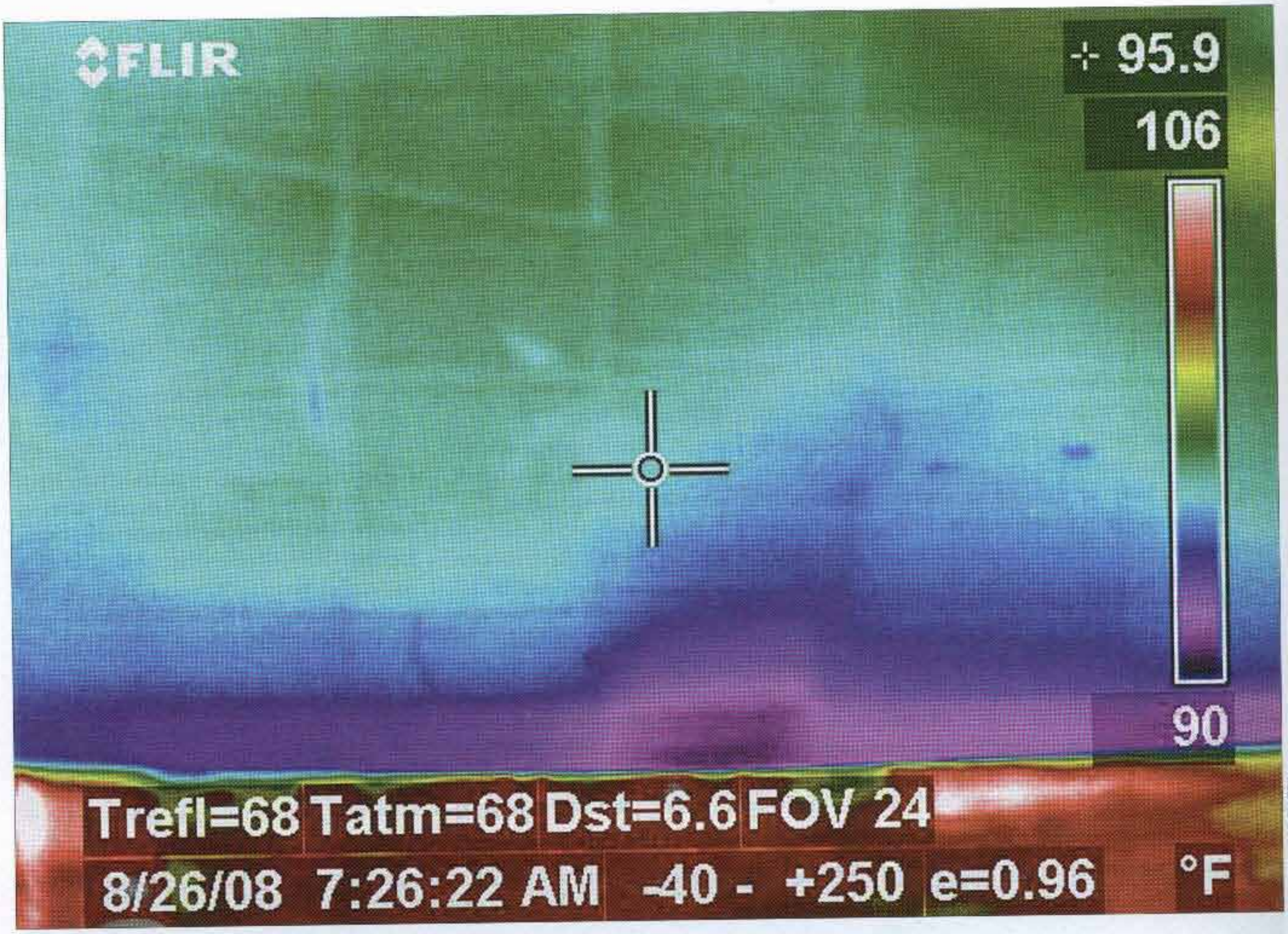
ADVANCED CONSTRUCTION AT GREEN MARINE
JOE ARTESE, INTERIOR DESIGNER
BOAT MANUFACTURING, POST-RECESSION
DIAGNOSING DARK COMPOSITES



TODD & ASSOCIATES

Diagnosing the Dark Composite

In Part 1 of two articles, we look at various methods for detecting damage in carbon fiber laminates.

by Ginger Gardiner

Above—The infrared image reveals an area of about 6' x 8' (1.8m x 2.4m) of a carbon-skinned/foam-cored racing sailboat's hull. Dark blue vertical lines indicate subsurface anomalies requiring additional ultrasonic inspection. Note the kerfs in the foam. The purple square at bottom center is a jackstand pad, roughly 1 sq ft (929cm²) in size.

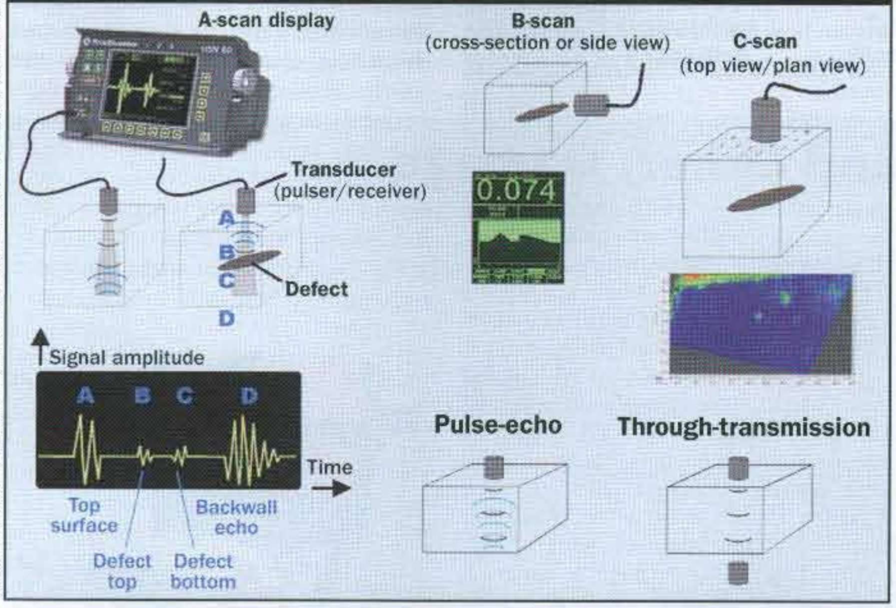
Carbon fiber has long since moved beyond masts and racing hulls. The material is now regularly applied to stringers and bulkheads both in large yachts and high-end production boats. Increasingly, too, carbon fiber laminates, in the form of a carbon/foam sandwich, are chosen by the U.S. Navy for prototype performance craft such as the M80 (24.3m) Stiletto multihull. *[See* Professional BoatBuilder *No. 97 Rovings column, page 12—Ed.]*

But what happens when carbon-equipped boats get damaged?

Composites in general are notorious for sustaining "hidden" damage after impact, when no visible damage is evident. With carbon fiber, the problem may be worse, because, unlike fiberglass and Kevlar—whose higher elongations to failure help *localize* damage—carbon's low elongation and high modulus help *transmit* loads through a structure.

So, how can you tell the depth and extent of damage without opening up the structure, or cutting holes?

Basic UT Technology and Displays



ESSENTIALS OF ADVANCED COMPOSITE FABRICATION & DAMAGE REPAIR, BY ABARIS TRAINING

Table 1. Pulse-Echo and TTU Capabilities

Pulse-Echo	TTU
A single transducer generates and receives.	Two transducers: one to send, one to receive.
Inspection with one-side access: excellent.	Requires access to both sides.
Detecting multiple defects: fair. Limited to finding the first occurring defect; sound-wave echoes interfere with deeper defects. (A phased array probe can make multiple defects visible from one side.)	Detecting multiple defects: very good. Can detect size and location of defects if they're in the sound path between the two transducers.
Defining defect depth: excellent. (But only if we know the sound-wave's speed through the composite.)	Cannot detect defect depth.
Curved surfaces: fair. Alignment of transducer to the part must be within 2° from perpendicular.	Curved surfaces: very good. Transducer can be up to 10° from perpendicular.
Detecting defects in multi-layered structures: fair.	Detecting defects in multi-layered structures: excellent.
More sensitive to small defects.	Less sensitive to small defects.

Ultrasonic Testing

UT technology has been around for more than 50 years, during which time it has become the predominant non-destructive testing method for composites in the aviation and aerospace industries. Developed from *sound navigation ranging*, or sonar, after World War II, ultrasonic testing sends high-frequency sound waves (that is, *ultra*sound waves) into a material and then measures the reflected wave signal. When a sound wave hits a discontinuity such as delamination, porosity, or water, a portion of the wave energy is reflected back from that surface.

UT equipment generally consists of a transducer probe and a display device. The transducer converts electrical energy into an ultrasound wave, transmits the wave into the test piece, receives the reflected sound wave, and converts it into an electrical impulse, which is then graphed on the display device.

- *A-scans* show a time-based waveform display. Today, handheld A-scan systems are the most common method to inspect composites out in the field.
- *B-scans* look at a composite from the side, in plane with the plies, and are shown as plots of surface distance vs. time.
- *C-scans* are plan-view grayscale or color mappings that are the easiest to interpret, but have historically required applying a *couplant* such as water to the part.

A couplant effectively transmits sound through the interface with the composite, because sound energy is not transmitted well through *air* at the frequencies usually employed for non-destructive testing; even a very thin air gap between the transducer and the test piece will make typical UT inspection impossible. Common couplants include water, glycerin, propylene glycol, and a variety of specially formulated gels. While not a major issue, applying a couplant adds further complication to the test, since some surfaces (especially porous, resin-starved, or heat-damaged areas) may be at risk for contamination.

UT employs two basic methods: pulse-echo and through-transmission, or TTU. The differences between the two technologies are summarized in **Table 1**.

UT Pros and Cons

Jonathan Klopman, a marine surveyor since 1989 and based in Marblehead, Massachusetts, has trained for and experimented with UT flaw detection for the past several years. He lists the following types of marine composite structures where, in his experience, UT successfully detects and quantifies damage: carbon spars (masts, booms, spinnaker poles), rudders, and carbon-skinned foam-cored hulls. He said that UT is also particularly effective in identifying delamination, as well as disbonds (so-called "neverbonds") deep within a ply stack. Klopman: "UT is a proven technology and gives repeatable results—when used by an appropriately trained operator. It offers a cost-effective method for quantifying damage, including size and depth, and can also identify construction details and manufacturing defects with extreme accuracy." Most aerospace references on UT agree with his assessment.

Like all non-destructive testing methods, UT has its limitations and drawbacks. Transducer probes are typically quite small, usually an inch (25mm) or less in diameter, so that inspecting large areas can be time-consuming. Moreover, significant training and experience are required before a UT inspector can reliably interpret the results.

Training

A UT inspector/surveyor must know how to choose the transducer frequency, as this determines the balance between penetrating power and resolution. According to Klopman, "Higher frequencies tend to provide better resolution. But they also reduce the

Detecting Heat (and Other) Damage

Reno, Nevada–based Abaris Training (see main text) made me aware of a new non-destructive testing technology developed specifically to detect lightning damage in carbon fiber composites. Lightning, of course, is a frequent culprit in carbon mast failures.

Fourier Transform Infrared analysis subjects a part to infrared light; FTIR then looks at how the light is absorbed and reflected. The process provides information about the chemical bonds in the molecules of the material. For example, several aircraft composites that had been exposed to high temperatures were measured with a device called Exoscan, a handheld FTIR analyzer made by A2 Technologies (Danbury, Connecticut). Obvious changes were noted, including an increase in the ester and perester bonds and oxidation of the epoxy backbone—all of which indicated heat damage and a correlating reduction in the composites' mechanical properties.

The Exoscan has been employed extensively to measure the degradation of composites due to heat, ultraviolet light, and exposure to chemicals. Including its data system and batteries, the unit weighs about 7 lbs (3 kg). It can also determine the degree of cure of a composite matrix. At a price of $35,000, the Exoscan is certainly not cheap; but according to A2 Technologies, no operator training is required, since the system comes with a detailed user's guide, and the software is considered user friendly. Even so, the company will work with customers as much as needed. A2 Technologies has produced more than 10,000 FTIR analyzers for a wide range of applications, and counts among its customers the U.S. military and Boeing (Seattle, Washington).

—*Ginger Gardiner*

The Exoscan, a handheld tool from A2 Technologies, measures damage caused by heat, ultraviolet light, and exposure to chemicals.

ability to detect deep flaws. Longer wavelengths—lower frequencies—let you look deeper into the material, but reduce the resolution with which you can detect results. Thus, knowing which frequency of transducer to choose is crucial to being able to detect damage."

Klopman cites other factors that affect results, among them: probe size and focal properties, the part's surface curvature and roughness, angle and location of the flaw with respect to the sound wave, and the material's attenuating properties (that is, its ability to weaken sound waves).

Randy Jones teaches non-destructive testing at Abaris Training, a Reno, Nevada–based school specializing in short courses in composites, aimed primarily (but not exclusively) at the aviation/aerospace industry. Jones added this about choosing the correct frequency transducer: "The normal range of frequencies for UT inspection in general—for composites and metals—is between 0.5 and 25 MHz; however, UT inspection of composites tends to work best at the extremes of this range.

Table 2. Effect of Transducer Frequency on UT Inspection of Composites

Frequency	Typical Spot Resolution	Typical Materials	Comments
0.5 MHz	0.31"–0.39" (8mm–10mm)	Thick laminates (closer to 1"/25mm thick), complex multi-layer composites	Will penetrate almost anything, but resolution is inadequate for many purposes.
5 MHz	0.19" (5mm)	Thicker solid laminates (0.2"–0.8" thick) (5mm–20mm)	Good compromise where max resolution is not required. Can penetrate most materials that are possible to test conventionally.
15 MHz	0.03"–0.07" (1mm–2mm)	Solid laminates, single-layer honeycombs	Gives results comparable in resolution to practical production tests.

Thick composites require very low frequencies, on the order of 0.5 to 1 MHz, while higher frequencies—more toward 10 to 15 MHz—are needed to resolve thin composites." (See **Table 2**.)

An operator might have difficulty understanding exactly what he or she is looking at in UT A-scans. "The inspection process is very much a matter of comparison. The inspector/surveyor is constantly scanning known baseline areas and moving in and out of suspect areas to determine flaw size, depth, and the nature of the flaw," Klopman said. He's spent many hours laminating *calibration standards*—that is, as-produced laminate samples without defects—as well as sample defective coupons that have known defects of the size, type, and depth targeted in a UT scan inspection.

Back to Randy Jones: "Just because you don't see damage when performing a UT scan, doesn't necessarily mean damage is not there. If you haven't selected the right frequency transducer, then you're not going to see what you're looking for."

Jones's first questions include: *What damage am I trying to find? What is the minimum detectable flaw size? What do I use as a standard that will make flaws in this part detectable?* He then employs "reference standards," which are laminate samples that have known defects at a known depth; these guide the inspector/surveyor toward the optimum frequency transducer that enables "seeing" the damage and providing the data required. If no such samples exist, then, as Klopman stated above, they must be made.

The Learning Curve

Mike Bergen, of Carderock (here's the long version: *fleet applications specialist in the Structures & Composites Department of the Naval Surface Warfare Center's Carderock Division, headquartered in West Bethesda, Maryland*) is part of a team that is summoned if anything goes wrong with a composite structure on a U.S. Navy vessel. For example: damage, or suspected damage, or quality-control questions relating to a prototype or classed ship. As Bergen explained, "Say there are some issues with a minor repair to an LPD-17 mast. I'll first support an in-house assessment of the structure. And then I'll secure the resources and talent if there's a need to repair it." [LPD *is the Navy's initialism for a ship designed to transport and land troops, equipment, and supplies by means of embarked landing craft, amphibious vehicles, and helicopters—Ed.]*

The Navy may be a strong believer in UT as an effective method of nondestructive testing, but Bergen agrees that inspector/surveyor training and experience are mandatory. He cautioned that the surveyor should have a working knowledge of the precise type of structure being inspected. "There was a case not long ago," he said, "where we suspected some dry spots in an infused, thin-skinned, carbon/foam structure. But we were having problems identifying those areas with UT." So Bergen went to a UT expert in the aerospace industry with samples of the structure's laminate construction, and brought along some samples containing deliberately produced dry spots. The expert scanned the latter—but didn't find the flaws.

Bergen said his team has gotten good at ultrasound A-scans to detect damage in very thick laminates (up to 3"/76mm) consisting of carbon skins sandwiching high-density (18-lb/cu-ft, or 288-kg/m³) balsa core—a composite similar to that used "in a lot of the DDG-1000 structures *[the Zumwalt-class destroyer currently under development].* But the thinner, lighter foam cores—which have more air and thus are more attenuating—along with thinner carbon skins, initially posed some problems."

Bergen's team is quickly gaining experience with the latter type of construction. They were called in to look at the M80 Stiletto, an 80'/24.3m prototype with an unusual hullform, whose fairly thin carbon skins are made from film-infused pre-preg *[in this case, a product made by SP/Gurit called SPRINT; see PBB No. 79, page 114—Ed.].* Those skins sandwich

Corecell foam core. "The Stiletto had broken loose from her mooring during a bad winter storm and sustained some damage at the waterline," Bergen said. Called to evaluate the situation, he recommended Bruce Bandos, of Carderock's Combatant Craft Department. "Bruce does all our NDT inspections," said Bergen. "I asked him to scan the inside and outside with a handheld ultrasonic tester. He typically does this by running a grid pattern in the area of concern, and marking a dot—with a non-wax-containing [felt-tipped] marker, like a Sharpie, to prevent surface contamination—as he reads anomalies on the A-scan screen." Bandos then literally connected the dots to show the damage outline. Bergen: "For the Stiletto, we mapped the area and found most of the damage was sustained on the outside, with minimal damage on the inside. And some debonding between the core and skins, mainly on the outer skin, but some too on the inner skin." Based on this assessment, Carderock was able to recommend a cost-effective repair method.

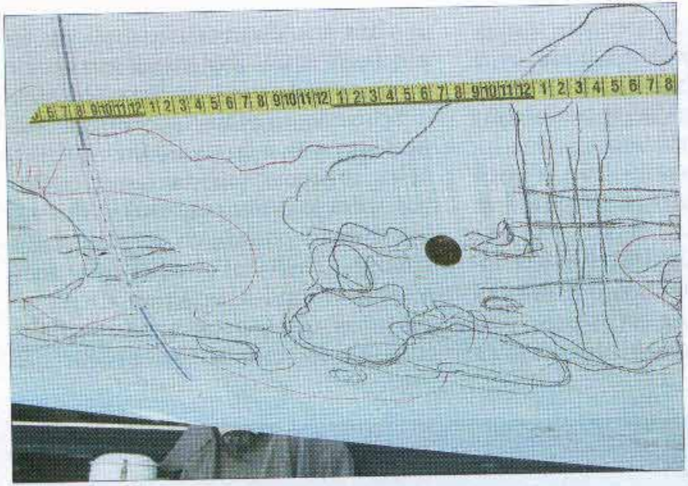
Given the growing number of naval vessels and structures made with carbon composites, Carderock is developing a baseline for thin-skinned, foam-cored construction, along with better methods for identifying damage and defects in core-to-skin bondlines. The Navy's new Manufacturing Technology Program has a requirement to continue working on these developments, and to manage technical projects approved by the Office of Naval Research. Bergen said: "We'll scan the hull when it comes out of the mold, before it sees any trauma—even just being loaded onto a trailer, for instance. That scan then provides us with a global map of the structure *as built*. And we will do it again immediately after builder's trials."

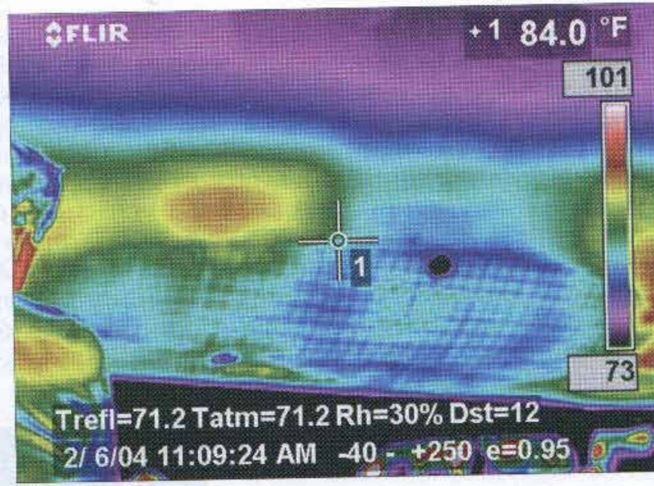
Bergen advised that for most carbon boats, the builder should have laminate samples made during construction, for UT inspection calibration samples, or baseline, since they represent the materials *and* build process in the original "undamaged" laminate. If the builder's laminate samples are not available, then calibration samples representative of the structure must be made.

Thermography

In thermography, a heat source (typically a flash gun or heat lamps) heats the part being inspected; an infrared camera detects the temperature change on the surface as the part is heated or as it cools. San Diego–based marine surveyor Todd Schwede has been performing thermography on marine composites for a dozen years. He said the laws of physics predict that energy will conduct through a material in a consistent manner. Damage or defects in a composite structure interrupt this flow of energy, and therefore show up on an infrared display. "Water, for example, acts as a heat sink, dissipating heat quickly. So it appears as a darker, cooler area on the computerized graphic interface," he said.

Schwede employs a 750°F (398°C) heat gun with a custom diffuser, which helps prevent "lingering" that causes hot spots and distorts results. This rig is mounted on wheels to produce a uniform 12" (30cm) swath that is easily moved around a structure. He typically has one person apply the heat (though sometimes two people are





TODD & ASSOCIATES (BOTH)

Left—*This 70′ (21m) ultra-lightweight ocean racer, built in Russia, has a high-density foam core sandwiched by two layers of mat and woven roving, with an outer skin of Kevlar/polyester resin. Seen here is damage detected by mapping the hull via thermography. (The black circle is a core plug.)* ***Right***—*Infrared image of same portion of hull. Dark blue lines indicate failed core, due to shear; the dark blue grid reveals water intrusion. Though we're looking at an aramid structure here, a carbon hull could be similarly analyzed.*

needed), and a thermographer to watch the monitor display. "We shoot the heat gun and read the monitor for anomalies simultaneously. Wherever we find an anomaly, we mark it on the hull surface exactly where it occurs. We map the surface of the structure indicating all anomalies, and then process the data once we get back to the office—to double-check our findings and perform analyses. It gives us a more accurate representation of the problems."

Schwede's FLIR P20 infrared camera captures temperature data for each pixel on the monitor, which he then analyzes with PC-based software.

Training and Experience

Schwede estimates that the number of people in the marine industry presently offering inspection services with the aid of thermography equipment ranges from 20 to 30. Many of those individuals, however, have not been specifically trained to detect damage in composite structures.

"Thermographers not experienced in 'shooting' composites can see thermal reflections and misread them as damage," he said. "For example, on one hull I was shooting, reflections from flagpoles 200′ [61m] away were appearing in the infrared image. Remember, the camera does not see optically; it only sees heat." Schwede added that he's learned how to shoot the same structure from multiple angles, which enables him to compare images and rule out reflections. "I'll map the surface in one color, move the camera 5′ or 6′ [1.5m or 1.8m] and change its elevation, and then shoot it again, mapping the anomalies in a different color. If an anomaly is present at all of the angles, then I know it's not a reflection."

Thermography requires developing a baseline of readings on an identical, undamaged laminate, just as UT does. Schwede obtains his baseline data by shooting the structure in an area away from the known or suspected damage, but still indicative of the laminate being examined. When Schwede first started using thermography, he developed a baseline database that included a wide range of virgin *and* intentionally defective samples. That was to give himself—and his clients—confidence in his findings. Or as he put it, "I've seen what the structure is supposed to look like. Now I know if what I'm finding is *not* the same."

Why Both IR and UT?

One reason for employing both infrared thermography and ultrasonic testing is simply the matter of scale. For UT, the immediate inspection area is directly under the transducer, typically described in millimeters and inches. With infrared thermography, Schwede describes an inspection window 10′ to 15′ (3m to 4.6m) wide and 8′ to 10′ (2.4m to 3m) in height. "We surveyed both the inside and outside of a 158′ [48m] infused hull, which at the time was the largest hull infused in a single shot." Hull construction consisted of a ⅜″-thick (9.5mm) outer skin, 2″-thick (51mm) core, and ⅜″-thick inner skin—about the maximum total thickness that Schwede's equipment can inspect. "The buyer wanted the hull surveyed as a pre-purchase condition. We completed the infrared inspection in five days using four people, and found a number of dry spots in the laminate."

Another benefit of thermography is being able to see a real-time color mapping, similar to a C-scan, of the structure being inspected. "We can capture digital stills while we're scanning a structure and also snap infrared thermographs, where each pixel contains real-time temperature data," said Schwede. He can also record the infrared scan as a video. This collection of user-friendly data has often proved helpful in answering an owner's or insurance company's questions quickly and definitively.

While thermography offers a relatively fast way to scan large structures, the basic handheld systems cannot provide a quantitative measurement of how deep the damage is. That's where following up with UT provides a more complete picture, giving quantitative details in the areas thermography has identified as having damage or defects.

Klopman believes that infrared thermography and UT cover each other's limitations quite well. "No single non-destructive testing technology will do it all," he said. "Knowing your specific goal in choosing inspection technologies is vital, as is knowing each one's shortcomings."

Price Shopping

When I asked Mike Bergen about thermography, he replied that he'd wanted to have Schwede inspect the underside of an LPD-19 mast, but it wasn't possible due to scheduling conflicts. Bergen: "We looked at thermography years ago, but back then we only had black-and-white readouts and a different method for heating up and cooling down that was difficult to use and get good results. The imagery and resolution are so much better now, and in color. The real issue is what is required in terms of man-hours, and how much the equipment costs."

Bergen gave an example: Bruce Bandos inspected an 85′ x 20′ (26m x 6.1m) boat in less than two days, singlehanded, armed with a basic handheld UT system from Panametrics (Waltham, Massachusetts). "So if thermography requires a crew of two to three people for one or more days, it won't be as efficient as what we're doing now."

By way of comparison, Schwede estimated a handheld infrared camera costs $8,000 to $9,000; and a typical thermographer's flat day-rate ranges from $1,200 for pre-purchase surveys to $1,800 for damage surveys, with extra personnel and expenses as additional costs. Randy Jones gave a range for typical portable UT systems of roughly $3,000 to $4,000 for thickness-gauge units, and $7,000 to $10,000 minimum for more accurate damage-detection systems. PBB

About the Author: *Ginger Gardiner is a 20-year veteran of the composites industry, where she has been a technical marketing rep (for Kevlar and Nomex), and owner-operator of a composites marketing consulting firm. She writes for* CompositesWorld.com *and other industry publications.*

In the next issue of Professional BoatBuilder, *she'll review: thermography with thermographic signal reconstruction; shearography; plus some promising new technologies. This two-part article was prompted by seminar presentations made at IBEX '08 in Miami Beach by marine surveyors Jonathan Klopman and Todd Schwede, who regularly combine thermal imaging and infrared testing in their practices. For an authoritative text on nondestructive inspection, see* Essentials of Advanced Composite Fabrication and Damage Repair. *It is available for purchase from Aviation Supplies & Academics Inc. (Newcastle, Washington) or through Amazon.com.*