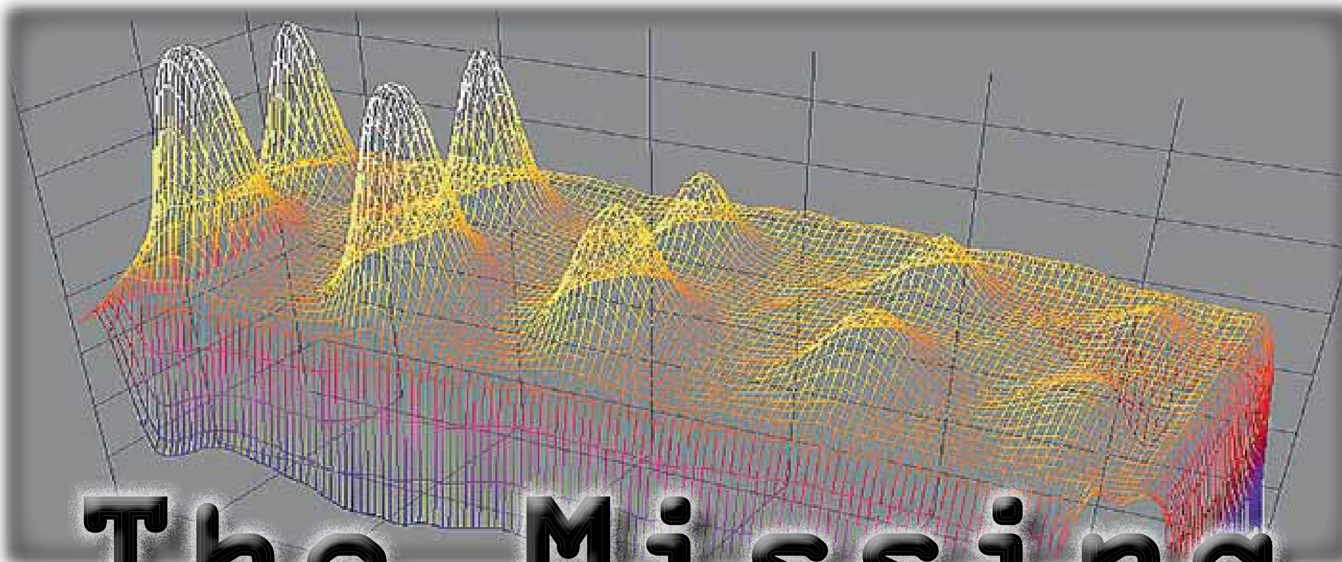


The Missing Dimension

Adding depth retrieval to infrared thermography provides the third dimension, *z*, in non-destructive composites inspections.

Text by Roby Scalvini

Graphics by the Marine Survey Bureau

Above—This graphic model of a composite test panel with flaws of known depth was derived solely from infrared (IR) thermography data run through a proprietary computer program. Post-processing the raw data minimizes the digital noise that may prevent the non-destructive testing technique from revealing the depths of flaws in a composite structure.

Every defect in a composite structure, be it a crack, a delamination, a bond failure, an air pocket, or porosity, has a three-dimensional character. Conventionally, those three dimensions are referred to as x (width), y (height), and z (depth). The problem is that most non-destructive examination (NDE) techniques currently available for the detection of defects within a composite structure are limited to either one or two dimensions. For instance, infrared (IR) thermography is extremely graphic in depicting x and y boundaries of planar defects such as delaminations, disbonds, and never-bonds (see the **sidebar** on the facing page), but does not provide depth, z. Conversely, given that the instrument is correctly calibrated, ultrasonic testing (UT) can be precise to within 0.3mm (0.012″) in determining the depth of a common planar defect in a composite laminate but can be limited in precisely defining the x and y boundaries. Although UT can be time consuming, operator dependent, and nowhere as graphic as a full-imaging technique such as IR, it remains a very useful tool—unrivaled in certain conditions—and an ideal complement, providing the depth (z) to the width (x) and the height (y) normally detectable by IR.

Composites inspectors now need to employ a multi-technique approach to add the third dimension, z, to a conventional IR examination. This process, known in NDE as "depth retrieval," requires dual skills for the inspector, who must be well versed in two completely different NDE techniques. Furthermore, some types of finish are not compatible with UT, and some laminates, such as those with a high Kevlar content, cannot be reliably inspected with UT (see the **sidebar** on page 46). And then there's the limit on the ability to document. For purposes of depicting and recording with certainty the size and location of a defect for future reference, the full-imaging techniques—IR, shearography, or X-ray—clearly outclass other NDE rivals such as UT, hammer tapping, etc.

Sizing Flaws in 2D

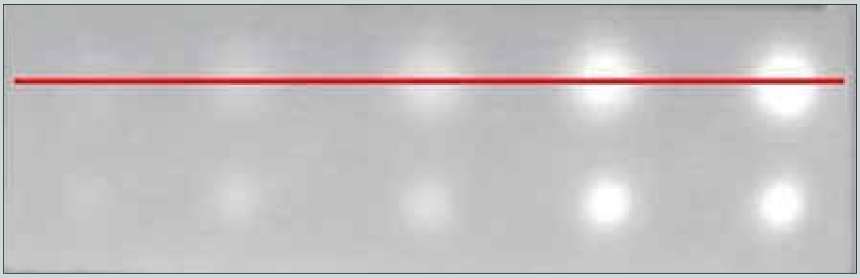
It can be challenging to accurately measure the size of a defect detected with infrared thermography (IR), especially if defects require a long heating time to be seen, and in materials with a high diffusivity (strong lateral dispersion). While algorithms for reliable automatic sizing have been developed, the sizing of a defect in two dimensions can be carried out with much more accessible and affordable technology.

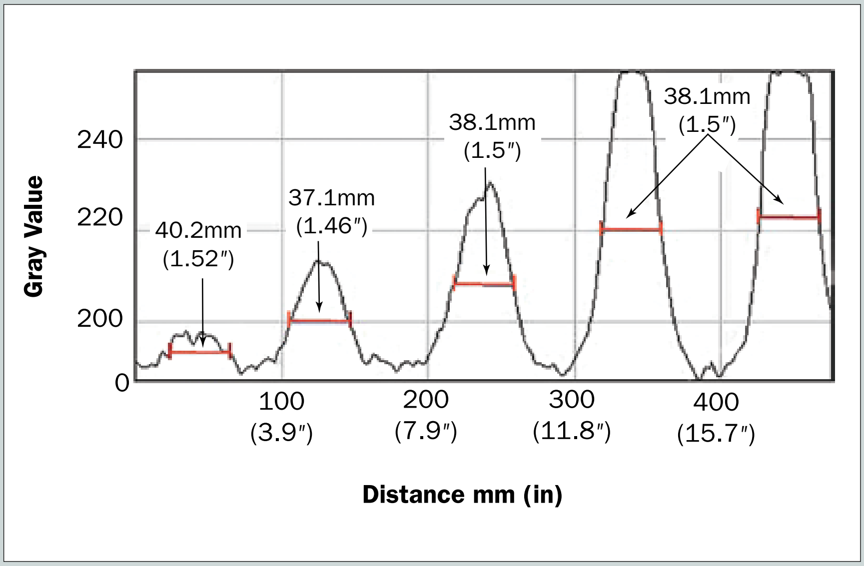
To start, a known length must be incorporated into the IR image to scale anomalies. For flaws with a low signal-to-noise ratio, the first step is to identify the maximum contrast image. This can be done either manually through a series of still photographs, or digitally through signal processing. Then, using image-processing freeware, the flaw within the chosen image can be plotted and measured.

For sizing planar defects, the "6-decibel (dB) drop" technique is employed. It is commonly used in other non-destructive examination (NDE) methods such as ultrasonic flaw detection.

Without going into the specifics of this technique, it's sufficient to know that to obtain the correct value, the size of a defect is measured at approximately half the amplitude of the contrast of the gray value between the flaw and the sound area surrounding it.

—Roby Scalvini



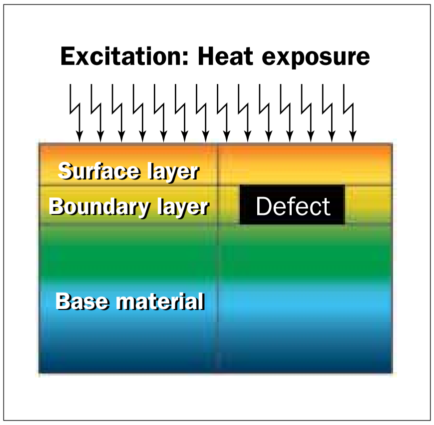


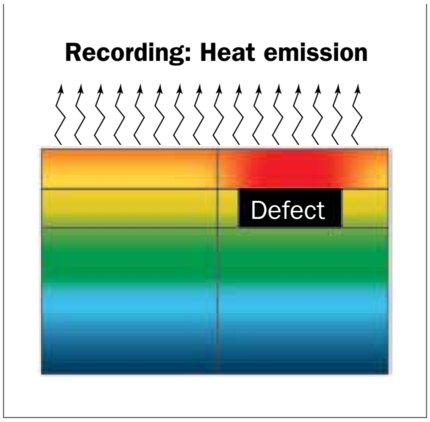
Top—*An IR image of a composite test panel with flat-bottomed holes drilled in the back. The red line indicates a plot through the upper row of "flaws," all measuring 38mm (1.5") in diameter. The known measurements of the panel were used as reference for sizing the flaws.* ***Bottom***—*A plot of the flaws shown in the IR image of the panel. Red lines at half the height of each peak indicate where size is determined employing the "6-dB drop" technique after applying image-processing freeware to measure the contrast in gray values between flaws and the surrounding composites. The results are remarkably accurate even for the barely visible flaws on the left of the panel.*

An All-IR Solution

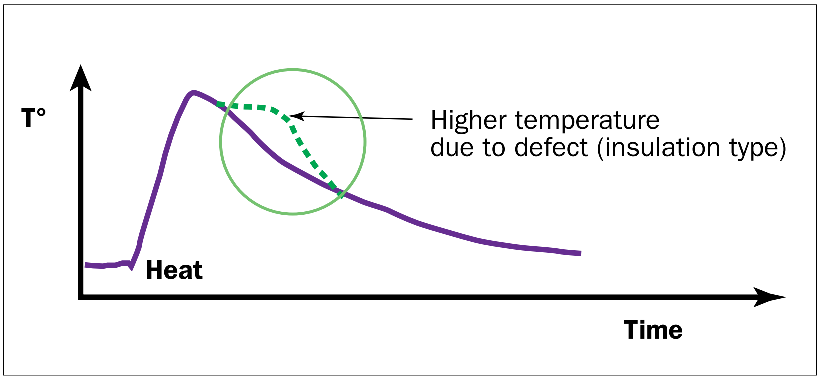
A more advanced way of solving the problem is to retrieve the depth of the defect by digital post-processing IR data acquired during inspection. To do so, we look not to one IR image but to the entire sequence of IR images recorded in response to a known thermal solicitation. But before we jump into the application of dynamic IR, let's review some basics of IR inspection (see "Designing for Testing," PBB No. 133).

Thermographic inspection of composite structures requires inducing a temperature gradient in the subject material, most commonly





Basic thermographic inspection technique relies on the fact that underlying composite defects such as delaminations or water intrusion absorb and reflect heat differently than does the sound material around them, making them visible to an infrared camera.



The purple line is a typical temperature evolution as heat is applied to, and then radiates from, a composite panel. The green line indicates the identifying behavior of a flawed section of laminate.

Although equipment intensive, IR testing can be carried out in the field, with lamps and an IR camera coordinated through a computer.

by convection (hot air), radiation (heat lamps), or conduction (heat blankets). There are also novel techniques employing microwaves and ultrasound energy to produce heat, but they are not fully developed or are not suitable for field application.

A composite part can be inspected either from a single side (reflection mode, where heat source and camera are on the same side), or from both sides of the structure (through-transmission mode, where the heat source is on one side of the part and the camera on the other). In practice, due to lack of access to both sides of a composite hull, nearly all active IR inspections are carried out in reflection mode.

Different defects behave in different ways when inspected in reflection mode. For example, planar delaminations act as thermal insulators and appear on the inspection surface as hotter areas, because the applied heat was prevented from dissipating into underlying laminates at the same rate as in the neighboring solid laminate. Conversely, if water is present, it will retain a good part of the induced heat energy and therefore appear on the surface as a relatively colder area.

To make a qualitative assessment in locating and sizing a defect in common glass-reinforced-plastic (GRP) composites, you need: an IR camera of adequate sensitivity and definition to produce still IR images; a convection-type heating source such as hot air; and a skilled operator.

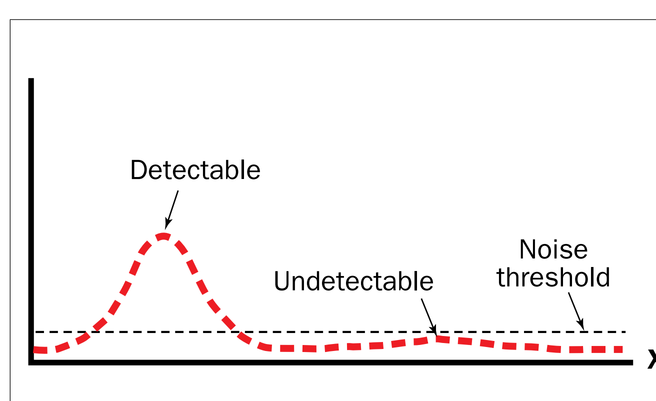
Detection and quantitative characterization of defects in advanced carbon-fiber-reinforced-plastic composites (CFRP) require a more sophisticated system (see “Diagnosing the Dark Composite,” PBB No. 123). The necessary package includes:

• **Data acquisition hardware.** This can be either a still IR camera with an analog video output combined to an external frame grabber (only if the camera processor provides at least 30 frames per second), or a full-on IR video camera with digital output. In spite of the considerable price difference, the two systems achieve surprisingly similar results. A good laptop computer for data storage and subsequent processing is also needed.

• **Heating source.** The rule here is to deliver as much thermal energy as possible in the shortest time, with an even heat distribution over the entire subject area, and without harming the part. Unfortunately, conventional sources do not distribute heat evenly enough, and/or are too slow to reveal certain types of defects. (Note that slow heating is ideal for detecting defects such as water ingression deeper in the core.) Advanced heating methods, such as those employed for pulsed and lock-in thermography, tend to employ radiating energy such as high-energy flash lamps. These ensure repeatability and uniformity of heating the subject area, but can be negatively affected by some coatings.

• **Software.** In practice, raw data are contaminated with digital noise and other signal degradations that limit or even hinder detecting defects in a laminate. Post-processing techniques, or signal processing, include a variety of tools to improve the data acquired in still images or video sequences. Signal processing can be as basic as manipulating temperature thresholds, contrasts, smoothing, or changing the color palette of still images through camera-specific software to improve the graphic representation of the image.

Computer-aided signal processing promises to lower the noise threshold in the IR data. Without it, the red signal is undetectable below the noise threshold.



The purpose of advanced signal processing is to increase the signal-to-noise ratio (SNR) and thereby enhance the visibility of defects, some of which would not be detectable amid the unprocessed noise. Advanced signal techniques programs—Fourier transform (FT), differential absolute contrast (DAC), proprietary thermographic signal reconstruction (TSR), and others—all employ very powerful algorithms to deconstruct and reform a sequence of IR images by recalculating each and every pixel, employing different proven mathematical models.

Because shop floor conditions are very different from those in a testing laboratory, signal processing is useful in countering the many variables such as: uneven heating; radiation losses; approximate values for thermal properties of the laminate inspected; and difficulty in estimating the *emissivity* of the surface due to irregularities or peculiarities of marine coatings that interfere during IR field inspections.

Depth Retrieval

Digital depth retrieval is the determination of the depth of a defect by employing either *time-domain* and/or *phase-domain* analysis of the recorded IR sequence. Speaking nontechnically, a time-domain graph shows how a signal changes over time; whereas a phase-domain graph shows how much of the signal lies within each given frequency and over a range of frequencies after a Fourier transform has been applied. We will focus on the time-domain technique.

The two parameters needed to perform such a calculation are the *time* of maximum contrast ($t_{C\max}$) and the *amplitude* of maximum contrast (C_{max}) at which a defect manifests after adequate pulse heating.

The time of maximum contrast is intuitively the moment on a time scale when a defect within a laminate shows the greatest contrast to the sound laminate around it. The amplitude of maximum contrast is the actual differential in temperature, or gray scale, at the time of maximum contrast between the defect and the adjacent sound laminate (see sidebar, page 41).

Spatial and time-filtering techniques, such as time averaging and smoothing, are first applied to the raw data to improve the signal-to-noise ratio, and reduce the margin of error in the depth-retrieval calculation that will follow.

Time averaging is an advanced post-processing technique, whereas individual frames of a video sequence are grouped in stacks of five images, and their thermal values merged/averaged into a single reconstructed image before further analysis.

The determination of the depth of a defect is solved by the following equation:

$$Z_{def} = A\sqrt{t_{C\max}}\,(C_{max})^n$$

Where:

Z_{def} is the depth of the flaw in mm beneath the surface.

$t_{C\max}$ is time in seconds necessary to achieve the maximum contrast.

C_{max} is the differential in temperature between the defect and adjacent sound laminate.

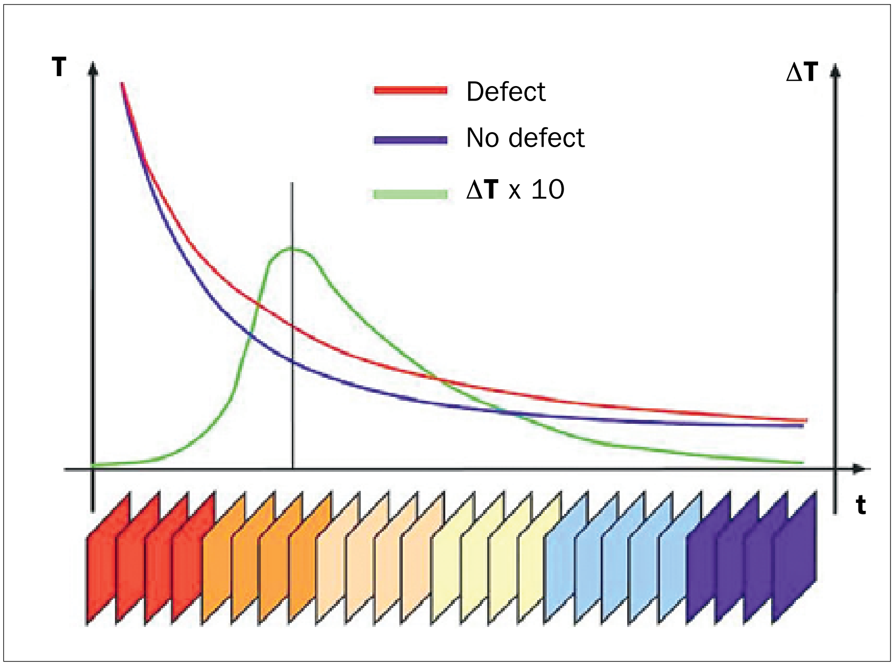
A and n are constants relative to the material under observation (determined from calibration/setup procedures).

As complicated as this theory may sound, its application in the yard is simplified by programs that perform the calculations for you. They don't come cheap, but the results they yield can be quite astonishing. At the Marine Survey Bureau (Palma de Mallorca, Spain), Carlos Lopez-Canepa has been instrumental in developing our in-house software customized for inspecting marine composites. The program covers a variety of signal-processing techniques and analyses, including digital depth retrieval.

For standard GRP composites it may be a bit of overkill, but for the more advanced composites increasingly common in our industry, this approach is becoming a necessity. In part this is due to the extremely high thermal *diffusivity* of carbon-fiber-reinforced plastic in comparison to fiberglass-reinforced plastic and other more conventional laminates. Thermal diffusivity is the rate at which heat travels through a material, i.e., the ratio of thermal conductivity to heat capacity.

In practical terms, high diffusivity means that the thermal response of a carbon-fiber laminate to a temperature gradient is exponentially faster than that of GRP. The time is so fast and the lateral dispersion so high that a number of defects can easily go undetected if inspected with conventional IR methods.

High diffusivity has a direct impact on the ability to detect defects in carbon-fiber laminates, especially those

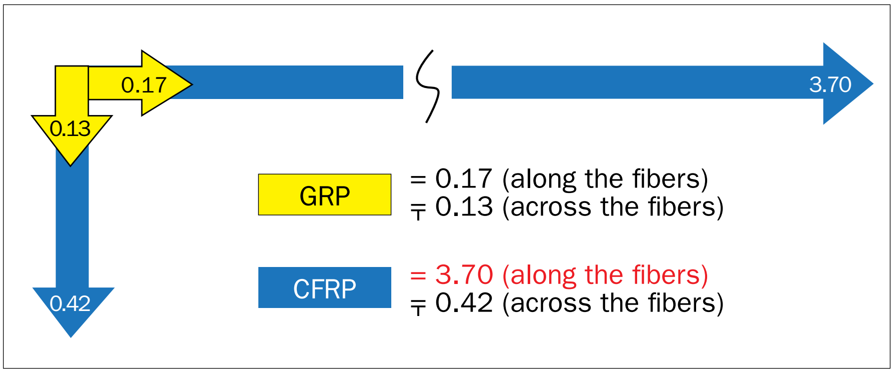


Time-domain graph showing the temperature evolution for two different points at the heated surface during cooling. The green line illustrates the difference between the red and blue lines magnified by a factor of 10 (ΔT x 10). Without this, it would be impossible to determine with the naked eye the exact position (frame) of maximum contrast between the temperatures of the flawed and nonflawed composites that is essential to calculating depth. The colored squares represent the individual frames of the test's video sequence.

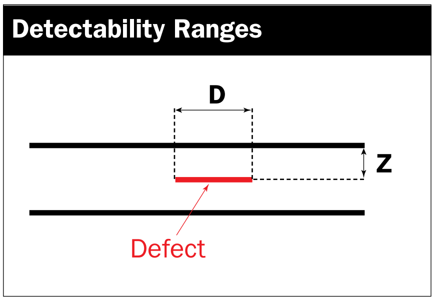
composed chiefly of unidirectional carbon fibers—in masts, hull internal reinforcements, etc. In-house testing and experience indicate that the detection of a flaw is limited by the ratio D/z, where D is the flaw diameter, and z is its depth in the laminate (see the Detectability Ranges figure, below right).

For GRP—2:3
For Kevlar—4:5
For CFRP—5:8

In order to be detectable, a delamination of a given size needs to be much closer to the surface of a carbon-fiber laminate than it would be in a comparable GRP laminate. Stated another way, a delamination sited at a given depth in a laminate stack needs to be much larger to be detectable in a carbon-fiber laminate than in its FRP counterpart.



Above—*Variations in diffusivity between glass-reinforced plastic (GRP) and carbon fiber-reinforced plastic (CFRP) mean that a delamination in the former is detectable far deeper in a laminate than the same delamination would be in the latter.* ***Right***—*The detection of any flaw with IR thermography is limited by the material-specific ratio D/z, where D is the flaw diameter, and z is the flaw depth.*



The Finish Factor

Infrared thermography measures infrared radiation emitted by the surface of an object. Because the physical characteristics of a surface dictate, in part, the amount of infrared radiation an object will emit, surface finish can fundamentally affect this technique's ability to detect underlying flaws.

The relative ability of a surface to emit energy by radiation is called *emissivity*. It is the ratio of emissive power by a particular material or its surface at a given temperature to that of a so-called blackbody, with no emission of infrared radiation.

Emissivity values are the outcome of three thermal effects: *absorptivity*, radiation absorbed by the material; *reflectivity*, radiation reflected by the material; and *transmissivity*, the fraction of radiation that passes through the material. A theoretically perfect blackbody would absorb all radiation energy directed at it; however, a real object can absorb only a part of it, with the remaining energy either reflected or transmitted through the material. By definition, values of emissivity are between 0 (a perfect reflector) and 1 (a perfect emitter such as the blackbody).

Comprehensive tables list emissivity values for different materials. Black electrical tape, with a known value of 0.98, placed on the test piece will provide a baseline for sufficiently accurate calibration of the IR camera.

In IR yacht inspections, factors that have to be included in the equation are reflection and color, because they can significantly alter emissivity and therefore the results. Different emissivity, unless accounted for in the calibration of the IR camera, results in false temperature readings; and as detection of defects relies entirely on the difference in temperature between sound and flawed areas, this can have a detrimental effect on the efficacy of such testing.

Emissivity values for smooth, shiny surfaces are generally lower than for those with irregular finishes. For example, polished aluminum has an emissivity value of 0.02, compared to dull, non-reflecting anodized aluminum, with a value of up to 0.77. This makes polished aluminum impossible to inspect by IR, as the metal acts like a perfect mirror.

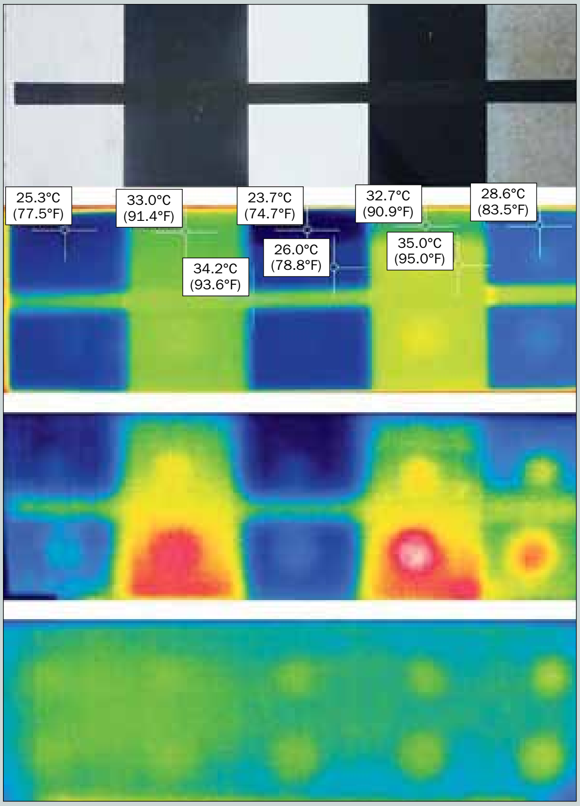
In addition to their low emissivity, smooth surfaces coated with gelcoat and shiny paint will reflect the surrounding temperatures like a mirror, which introduces the risk of mistaking reflections for flaws.

Emissivity also changes with color. Black paint has a value of 0.95, while white paint has a value of only 0.84. Color will play an added role in determining the rate of heat transfer into a composite structure, especially if the heat is introduced by radiation (lights/lamps) rather than by conduction (heat blankets) or convection (hot-air guns). Dark colors will heat up faster than light colors, affecting the time required to establish the temperature gradient required for IR testing.

As a general rule, the higher the emissivity value, the better the results of an IR inspection. Unfortunately, fine yachts tend to be white and shiny.

Countermeasures to improve emissivity values and limit the influence of reflections include coating the inspected area with a non-reflecting coating, and/or shielding it from its surroundings to avoid reflections. Inspecting from different angles will also reduce the risk of erroneous readings from reflection interferences. And if the

Continues on page 48.



Top—*This GRP test panel is painted with common marine finishes from left to right: white antifouling, dark antifouling, white Awlgrip, dark Awlgrip, and uncoated GRP. Note the black electrical tape across the full panel.* ***Upper middle***—*An IR image of the same panel exposed to natural sunlight reveals the correct temperature of 34.2°C (93.6°F) only on the black tape.* ***Lower middle***—*An IR image of the same panel heated by halogen lights reveals defects most distinctly in the darker areas.* ***Bottom***—*An IR image of the same panel heated with a heat gun. Note how defects on the left are obscured by the textured antifouling's retention of heat.*

image will be subjected to advanced signal processing, the reflection can be eliminated by a digital process called cold-image subtraction; as its name indicates, it eliminates from all images of a video sequence the reflections present prior to inducing the temperature gradient.

Working at night or in a covered area and choosing the appropriate heat source to introduce the temperature gradient will reduce the effects of finishes on the ability to detect defects.

To illustrate the role of surface finish in thermography, we carried out two simple tests: one employed three soft-drink cans filled with water of different temperatures (hot, ambient, and cold); in the other, one side of a monolithic FRP test panel was finished with three different common marine coatings, and the backside was peppered with calibrated holes of the same depth.

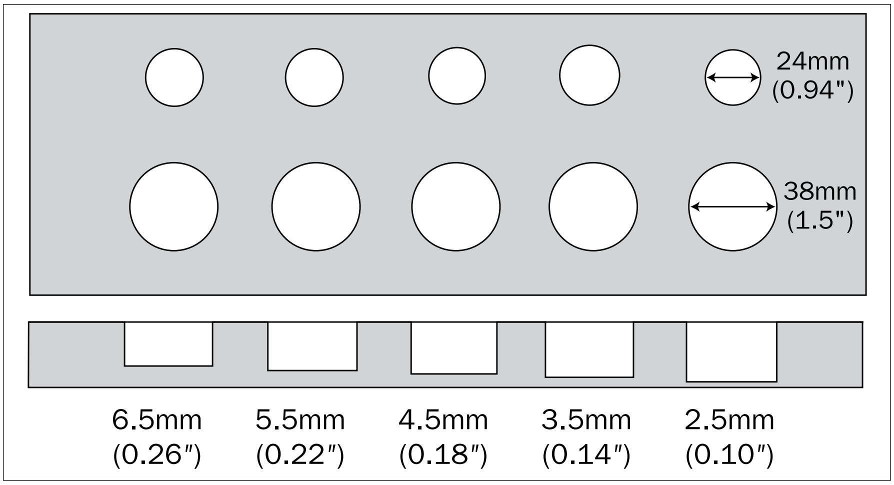
Continues on page 50.

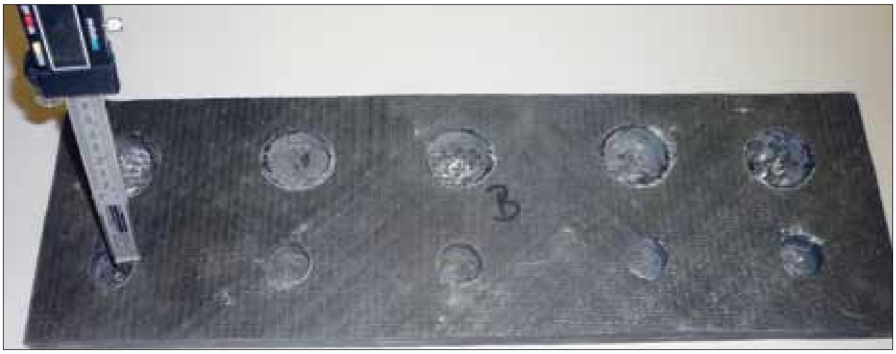
Test Case

To better understand the retrieval of depth of a defect by digital means, we conducted a test employing the following equipment: a test panel with known defects, a suitable heating source, an IR camera, and signal-processing software.

The panel was an epoxy-carbon-fiber monolithic laminate measuring 500mm x 160mm x 17mm (19.7″ x 6.3″ x 0.7″). In one side we drilled flat-bottomed holes (FBH) representing defects of differing diameters at different depths in the laminate, when tested from the intact side. We measured the depths of the holes with a digital depth gauge and also with A-scan ultrasonic testing equipment.

The inspected side was subjected





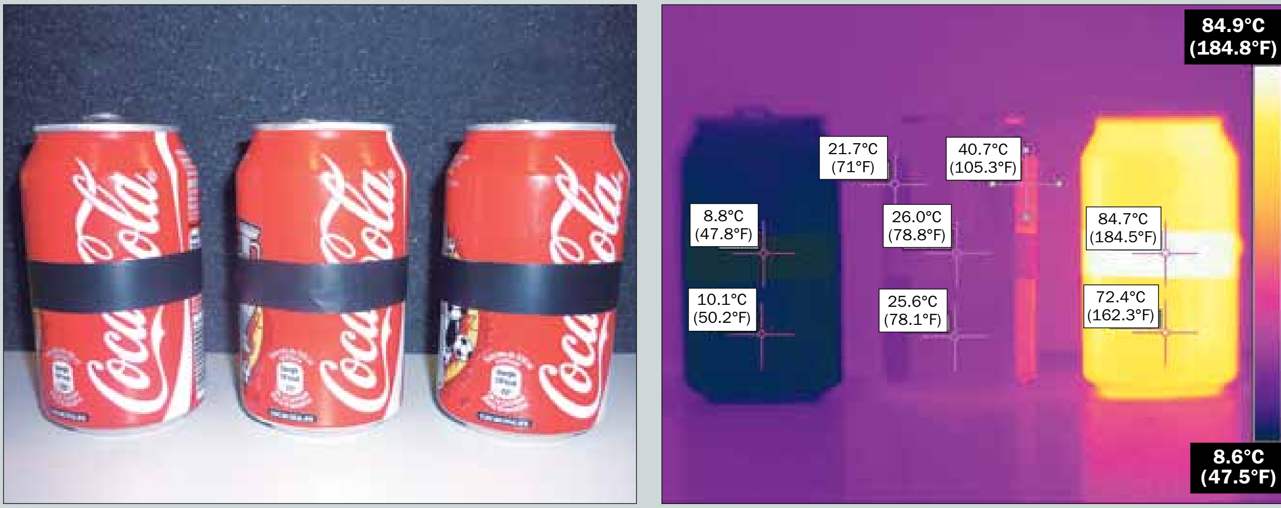
Top—*A monolithic carbon-fiber-epoxy test panel was designed with flat-bottomed holes in two different diameters drilled into the back of the panel at five depths.* ***Bottom***—*Verifying the depth of holes in the actual panel.*

Continues from page 48.

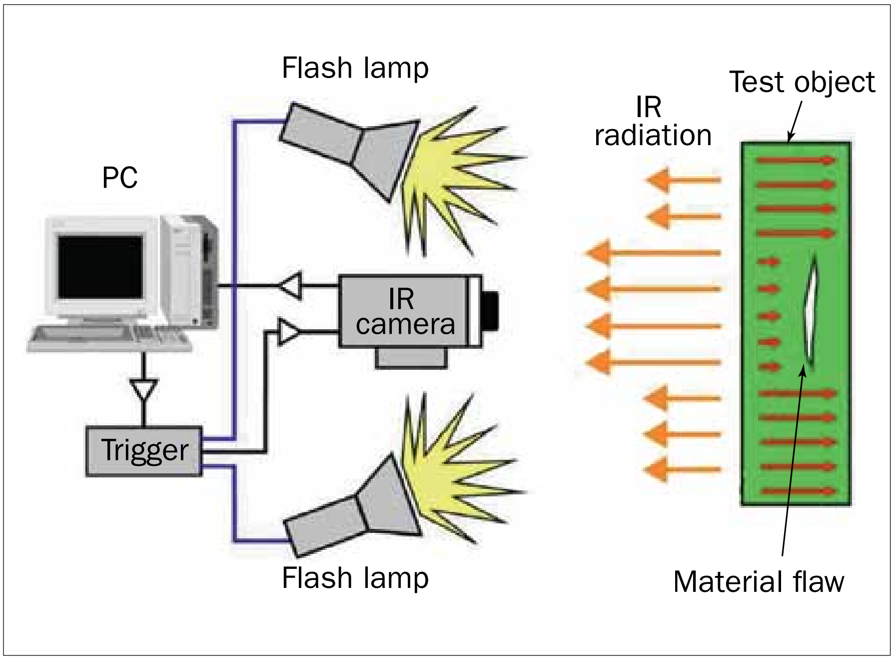
We inspected the test panel under uniform sunlight, and after heating by radiation (halogen lights) and convection (hot air guns).

In both examples, we employed electrical tape to indicate baseline temperature values. The differences recorded by the IR camera are quite surprising.

—*R.S.*



Three soft-drink cans containing different-temperature water: hot, ambient, and cold. Note that the temperatures recorded through thermography are accurate only in way of the black electrical tape on each can. The other readings are incorrect due to coatings or the reflections of adjacent cans, which project a cold area to the left of the center can and a hot area to the right.

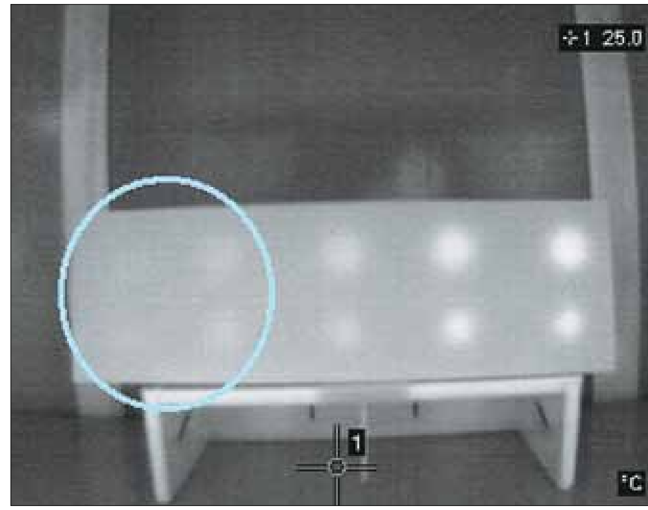


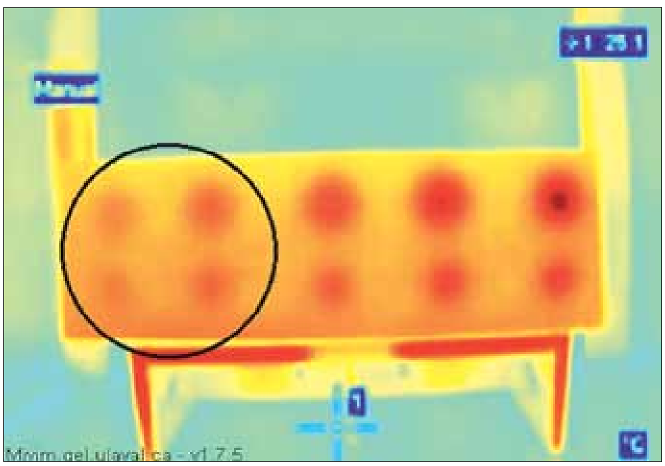
Apparatus for the test included a FLIR A40M IR video camera connected to a laptop running custom signal-processing software. Otherwise, it was a standard setup for pulse thermography as show here.

to IR testing in reflection mode. Heating was from four photographic-type Xenon flash lamps, with a total output of 9.6 kW, and a flash duration of approximately 5 milliseconds. This produced a sharp thermal wave (pulse) that increased the surface temperature of the panel by less than 5°C (9°F) for a fraction of a second.

A FLIR A40M IR video camera was employed to acquire the data, with digital output connected to a laptop computer equipped with our custom signal-processing software. The video sequence was time averaged and smoothed by employing a Gaussian filter to generate a 3D matrix for further processing. The contrast profile was then plotted for each defect, and their depths were automatically calculated. The test proved that the depths calculated by this method are within the margins of precision provided by ultrasonic A-scan (about 0.3mm, or 0.012″).

In further analysis with software programmed with the known relation between time of maximum contrast and depth under the heated surface, it is possible to generate images of each ply, or range of plies, and assemble them into a graphic 3D map of the defect.

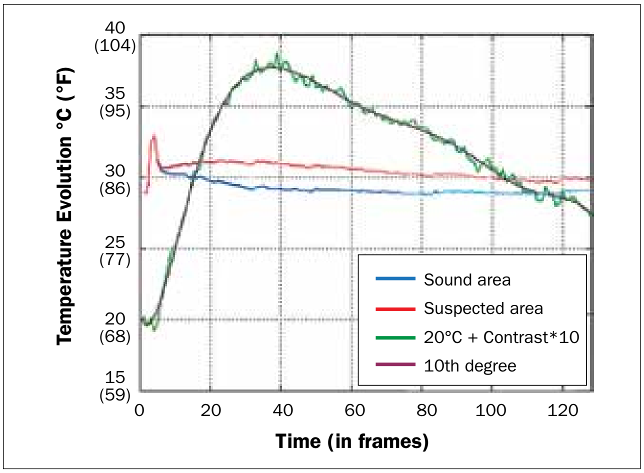


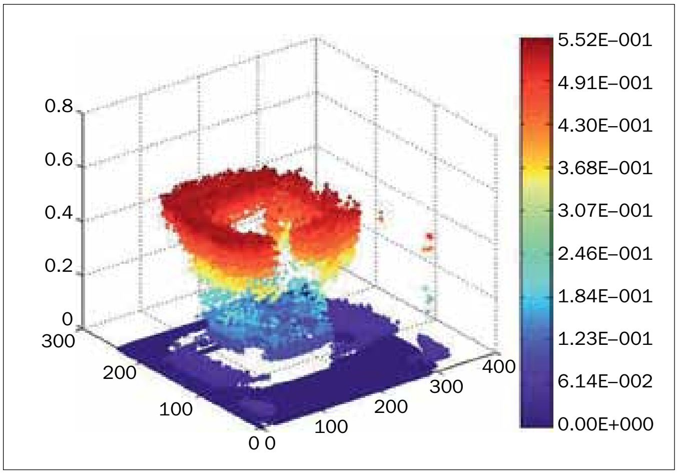


*Images from the test panel include, **top left,** a photograph; **top right,** raw IR; and **left,** post-processed IR. Note how much better the definition of deeper flaws on the left of the panel appears in the last image.*

Conclusions

The combination of low laminate heating (which allows prompt recovery of the inspected area and adjacent panels), large footprint (up to almost 1m^2/10.7 sq ft), and enhanced signal





Left—*The test for each defect yielded profiles similar to this one, which plots the time and amplitude of maximum contrast.* ***Right***—*Applying that information, it is possible to generate a 3D rendering of each ply or a range of plies in the structure to reveal the true shape and depth of a laminate flaw.*

processing makes pulse IR thermography ideal for inspecting in three dimensions large structures built in advanced composites. Note that depth retrieval by IR alone requires that the equipment be carefully calibrated to the test piece in order to yield accurate z-axis readings; and uniform, repeatable heating plays a significant role in obtaining precise results. While these factors make the technique better suited to quality control during manufacturing or routine inspections for vessels in service than for one-time troubleshooting in the field, with due care we have been able to successfully apply the technique in the yard as well.

About the Author: *Roby Scalvini, the principal surveyor at the Marine Survey Bureau in Palma de Mallorca, Spain, is a specialist in advanced nondestructive testing.*