Composite materials, specifically carbon composites, offer advantages over metals including stiffness, specific strength, and weight reduction\(^1\)-\(^3\). Carbon fiber-reinforced polymer (CFRP) matrix composite structures are increasingly used in next-generation aviation and missile systems. Lightweight composites improve fighter aircraft fuel economy, increase flight times, enhance lethality and/or increase flight velocity. Despite these advantages, composite structures are sensitive to impact damage caused by accidental tool drops, hail storms, flying birds, routine operation, and/or ballistic threats, all of which can severely reduce structural integrity. For example, a dropped spanner or runway debris can generate localized areas of damage that are frequently difficult to detect with the naked eye. Such barely visible damage can result in premature catastrophic failure.

Projectile impact can generate large areas of delamination, fiber fracture, fiber buckling, and matrix cracking\(^4\)-\(^5\). In most cases, fiber composites are able to absorb the impact energy and transfer it to the matrix. A low velocity impact is known to produce delaminations between the layers with no visible surface manifestation. Such delaminations may grow in service causing severe stiffness reduction in the structure. Test results from composite coupons subjected to low energy projectile impacts show reductions in residual tensile and compression strengths of up to 50\(^\%\)\(^4\)-\(^7\), conditions resulting in a complex fracture process. Impact damage is one of the most significant damage types because it can initiate delaminations, which greatly reduces compressive and fatigue strengths of a composite component. These situations drive the development of nondestructive testing (NDT) techniques in the aerospace industry where composites are used in many critical applications.

**NDT methods used to assess impact damage**

NDT is important for evaluating laminated composites where delamination and internal cracking are possible failure mechanisms. Fast, efficient techniques are required to quantify and assess the condition of a composite, as well as the presence and extent of any surface damage. Accurate damage assessment is critical to prevent premature failure and extend service life. Commonly used NDT methods include ultrasonic C-scan, mechanical impedance analysis, shearography, x-ray refractography, and dynamic or transient thermography.

**Dynamic, or transient, thermography (TT)** uses an infrared detector to record surface temperature decay on a surface subjected to a short heat pulse\(^9\) from an external heat source, such as a quartz lamp. A subsurface defect can appear as either a hot or cold spot in the thermal image. The rate at which the surface temperature returns to the baseline, or steady state value, varies with the material composition and the presence of defects. TT was used to detect and quantify damage in thin (~2 mm) CFRP laminates\(^9\),\(^10\).

Thermography has the advantages of providing noncontact, rapid inspection, single-side inspection, and can cover wide areas of flat and curved parts. The applied heat is typically less than 15\(^\circ\)C above ambient. The resulting tempo-

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**Assessing Impact Damage on Composites Using Line Scanning Thermography**

- **Obdulia Ley**
- **Manny Butera**
- **Valery Godinez**
  Mistras Group Inc.
  Princeton Junction, N.J.

- **Simon Chung**
  Materials Sciences Corp.
  Horsham, Pa.

Line scanning thermography can be used to identify regions in composites containing delaminations from impact, providing fast, easy to interpret results.
rational temperature response is fitted to a theoretical model to quantitatively measure thermal diffusivity or thickness. TT has the advantage of faster imaging, but is limited to near surface (within ~1 mm) inspection. However, because most damage that follows impact is concentrated near the surface, TT is a convenient method to study and characterize impact damage.

**Thermal effect of a delamination**

Damage generated in a laminate composite from low velocity projectile impact produces delaminations that affect heat propagation and generate discontinuities, or a region of increased heat resistance. Consequently, dynamic thermography shows the region affected as a hot spot. The temperature rise associated with a delamination is the result of material properties, severity of the discontinuities, the amount of heat applied, and the time at which the temperature is recorded after heat application. Figure 1 shows the progression of the heat diffusion after heat application.

Analyses of the dynamic thermal response of various low velocity impact sites are discussed in this article. Impacts were made using different energies, and relationships between the area affected and the maximum temperature detected are associated to impact characteristics. The focus is on understanding how heat diffusion after heat application affects the size of the area showing the damage generated by impact. Thermography was used for the study because it can detect discontinuities and defects in composites, and the signal produced by a defect is high in thin materials.

**Line scanning thermography**

Most dynamic thermography techniques use a stationary thermal imager and are limited by the requirement of analyzing one section of the sample at a time[11]. This increases inspection time of large areas due to repositioning of the heat source and IR camera. The thermal imager is placed farther away from the surface to inspect large regions, but this limits the thermal image resolution, or the number of pixels, in the image used to represent a defect. This article discusses the use of line scanning thermography (LST) to inspect impact damage regions in different composite structures.

LST is a dynamic thermography technique patented by NASA[12, 13]. It applies heat along a thin line, which is swept from edge to edge of the surface being inspected. The IR camera moves in tandem with the heat source at a set speed, and captures the thermal profile of the sample after heating. A diagram of the basic setup is shown in Fig. 2, where the camera's field of view is restricted to an area of the sample surrounding the heat application region. During the scan, the temperature of the region swept by the heat source increases, whereas the surface temperature of the region in front of the heat application remains constant. LST requires optimizing scanning speed and heat intensity to match the heat diffusion in the material being studied. A thin material with good thermal conductivity requires fast scanning speed and significant heat deposition, while a thick material or a material with lower thermal conductivity requires a slower scan with a reduced heat deposition intensity[14, 15].

LST produces a series of images of the entire scanned area. Each image shows the surface temperature distribution at a given time after heat deposition. Images are generated by defining an observation window or a given pixel line from all frames acquired during the scan. The final image or image of the entire scanned area is formed by stacking the selected pixel line from captured frames. When using images with a sensor resolution of 240 x 320 pixels, a maximum of 240 images of the entire area can be constructed. The time elapsed between consecutive pixel lines depends on scanning speed and the camera frame rate. Figure 3 shows an example of images that can be generated using LST following heat deposition; images show the same scale, and were generated using different observation windows.

LST scans were performed using our laboratory set up, which performs vertical scans of up to 5 ft long and 16 in. wide. The system uses a cooled infrared camera working in the mid-wave infrared range (3-5 μm). A 16-in. long quartz lamp deposits 200 W/in. of energy at maximum operating power. During LST scans, energy is deposited over the surface of interest in the form of a 0.25 in. thick line. Heat deposition is controlled as a percentile value of the 200 W/in.
maximum deliverable power. The surface to be inspected was positioned vertically facing the heat source (Fig. 1).

**Summary of impact-damage studies**

Several test coupons and structures subjected to different types of projectile impact were evaluated using LST scans. In most cases, damage observed with LST is compared with the area observed using ultrasonic scans. Parts and components discussed here represent light composite armor and different types of flat laminate composite panels commonly used in aerospace applications, such as honeycomb panels.

**Honeycomb panels with carbon/epoxy composite**

Nine 6 in. × 6 in. aluminum honeycomb test coupons with carbon/epoxy laminate composite faces were studied on both sides using LST and immersion UT. For LST scans, three samples were studied in a single scan 28 in. long. Scanning speed ranged between 2 to 0.25 in./s. Fast scans allowed observation times of up to 6 seconds after heat deposition for a scanning speed of 2 in./s, and to 50 seconds at 0.25 in./s. Slower scans were performed to try to observe information from the honeycombs. However, most damage generated was very superficial, and a speed of 1 in./s was selected to inspect all test coupons. Figure 4 shows both LST images and UT C-scans obtained for six of the samples scanned. Areas showing delamination in LST and UT scans were calculated using a cluster analysis algorithm. Areas detected by LST were consistently slightly higher than those found using immersion UT. In this case, the region affected in the C-scans was defined when the UT amplitude fell below 15%.

**Composite driveshaft**

A belt-wrapped composite tube was impacted at various energy levels using a free falling weight (25-mm diameter steel impact nose). Composite driveshafts provide higher critical speeds allowing a higher maximum rpm with less vibration. Their lower weight reduces rotational inertia and allows faster acceleration and deceleration. A composite driveshaft provides a safer alternative that will self-destruct and disintegrate, minimizing damage of the...
surrounding parts in the event of problems.

The entire surface of the shaft was scanned using three LST scans covering 120 degrees each. Figure 5 shows thermal profiles of the tube for each of the three sections (denoted as Run 1, Run 2, and Run 3). Regions that were impacted are evident in the form of thermal gradient. The magnitude of temperature difference for a given time \( t \) after heat application seems to be proportional to the magnitude of the damage and the magnitude of the force of the impact. Additional details of this relationship are provided in Ref. 10. Impacts were performed in the low velocity range, and were done at different energies ranging from 90 to 23 ft-lb. The skin of the material broke at impact energies larger or equal to 64.5 ft-lb. The following analysis of thermal images is based only on the impacts that did not break the skin of the composite cylinder. UT was used to identify the extension of the damaged region. The region (showing variations of the reflected coefficient) was marked on the surface, and was observed in the thermal images.

The scanning parameter combination selected for LST (1 in./s scanning velocity and heat deposition or intensity of 25 %, or 50 W/in.) were selected because they provided good thermal contrast, as well as sufficient observation time of the area under consideration. The earliest observation time corresponded to 2.82 s, just as in the first configuration, and the latest observation time was 11.55 s.

In addition, the second set of impacts show that the maximum temperature observed is proportional to the impact energy. To see the effect of the selection of observation time over the size of the hot spot, it was necessary to define a minimum temperature change based on the average temperature of the background region, or a region not showing hot or cold spots; this is defined as 10 % over the average background temperature \( T_{\text{bkg}} \), or:

\[
T_{\text{min}} = (1.1) T_{\text{bkg}} \quad \text{(Eq. 1)}
\]

Once \( T_{\text{min}} \) was defined as a function of time, it was seen that the area affected is small at early observation times, but encompasses only the region more severely damaged, because the temperature detected is high. Temperature drops in the affected area with increasing observation time and the area increases due to diffusion. The affected area grew following a linear relationship with the observation time (Fig. 6).

**Composite hardbacks**

Several hardbacks that form part of a missile launcher were inspected visually by LST and using immersion ultrasound. The time required to inspect the entire front surface of the hardback using UT was about 15 minutes using a heavy-duty high-speed industrial immersion system.

LST scans and time needed for implementation ranged between 0.25 to 0.75 in./s (200 to 75 s). Each scan covered the entire front surface of the hardback. To perform LST scans, the sample was set vertically in the laboratory set up, with the aft of the part placed at the bottom of the scan. Following heat deposition, observation of the surface temperature distribution after 16 and up to 67 seconds produced by scans at 0.5 and 0.25 in./s showed regions with different thermal signature (hot spots). The 0.25 in./s scanning speed is used to assess the state of the components studied. Figure 7 shows a comparison of C-scans and LST images of the structures. Both techniques show damage around the same areas (red areas in C-scans and white, or bright, areas in LST thermal image). Ultrasonic C-scans show more detail about the damage regions, but the LST technique is able to determine the region affected in a single scan that lasts 200 s.

Continued
Fig. 7 — LST image of composite hardbacks that form part of a missile launcher produced by the difference between surface temperature early and later after heat deposition (top), and corresponding C-scans obtained using immersion ultrasound (bottom). Both LST and UT show damage around the same areas (red areas in C-scans and white or bright areas in LST thermal image). LST images show the mirror image of the part or area scanned.

Conclusions

LST provides a method to inspect large areas in a short time, due to novel scanning protocols and image processing. The success of LST depends on proper optimization of scanning parameters, namely heat deposition and scanning speed, which should be set to match the heat diffusion in the structure.

Because LST deals with a dynamic process, the observed size of the damaged region depends on the time after heat application at which the specimen is observed. In LST scans, surface temperature is higher a short time after heat is deposited, and the area showing the hot spot corresponds to the area experiencing more severe damage. Given time for heat diffusion, all areas affected show an increased temperature, and are comparable to those selected using UT. In all cases, impact energy was associated to the magnitude of the temperature increase detected using LST at any observation time.

LST and UT manual or C-scans are capable of detecting the region affected by...
impact and, in general, provide similar results in terms of areas affected. For the systems studied, LST was easier to use, provided results more quickly, and that were easier to interpret.

References

For more information: Obdulia Ley, Mistras Group Inc. 195 Clarksville Rd., Princeton Junction, NJ 08550; tel: 609/716-4042; email: obdulia.ley@mistrasgroup.com; www.mistrasgroup.com.