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Understanding carbon/epoxy impact damage with infrared thermography

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Monitoring online impact tests via the surface-temperature variation of a laminate enables information to be obtained about the initiation and propagation of impact damage.

Composite materials, particularly carbon-fiber-reinforced polymers (CFRPs), are increasingly finding application in the construction of aircraft primary structural components. This is thanks to their favorable strength-to-weight ratio.[1] CFRPs are, however, vulnerable to impact damage. The most significant impact damage is that sustained from low-energy collisions,[2] which can give rise to critical damage inside the material thickness without causing any noticeable deterioration at the impact location. As such, potentially dangerous vulnerabilities can go unnoticed.

Impact damage in composites occurs as a result of a range of complex mechanisms, and can have a large number of effects.[3] These variables are not completely understood and cannot be modeled at the design stage. The design of new composites must therefore be accompanied by adequate testing. Evaluation of new materials is generally performed based on criteria of energy and force, or on a multiple-parameter configuration.[4] Among these, one of the main factors is damage extension vs. impact energy. This is often assessed via specific impact tests that can identify the energy that has caused delamination of a given extension. More specifically, such tests consist of impacting the laminate at a given energy and subsequently evaluating (in a non-destructive way) the induced damage extension. Impact energies are increased until the pre-set delamination has been reached. This approach requires time and is often not very accurate, since very thin delaminations are difficult to detect using current non-destructive testing techniques.

In our work, we have demonstrated that it is possible to monitor the surface of a laminate directly during impact. Our method employs an infrared (IR) imaging device to obtain information about the material behavior under impact.[5–8] We carried out impact tests with a modified Charpy pendulum, which allowed enough room for the IR camera to be positioned to the rear of the specimen surface (i.e., opposite the impacted surface): see Figure 1. Each specimen is placed inside a special fixture that includes two large plates. Each plate has a window—with dimensions of 12.5 × 7.5cm—to allow the hammer (attached to the Charpy pendulum) to impact upon the surface of the specimen from one side, and to enable an optical view (for the IR camera) from the other side.

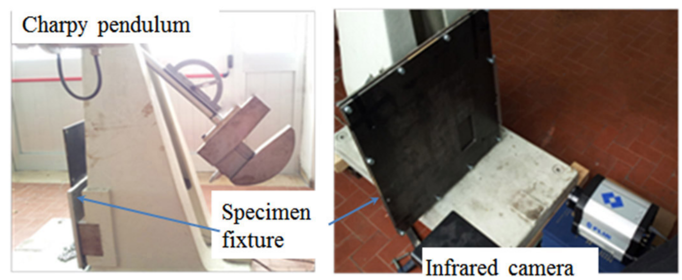

Figure 1. *Test rig for investigations into the effect of impact energy on the carbon-fiber-reinforced polymer (CFRP) specimen. The impact energy is set by adjusting the falling height of the Charpy pendulum (left). The infrared (IR) camera (right) is focused on the specimen surface through the window in the lodging plate, and thus acquires thermal images during the impact event.*

The IR camera remotely visualizes the surface-temperature variations, coupled with the mechanical-impact-induced stresses, and collects sequences of images over time. Our system thus enables thermal-image sequences to be obtained during the impact event, and complete visualization of the thermal-effect evolution (with respect to the ambient temperature). The acquisition begins a few seconds before the impact and lasts for some time after. We have recorded a video[9] showing an example of material behavior under an impact energy of 2.8J. From this animation, material damage can be ascertained by

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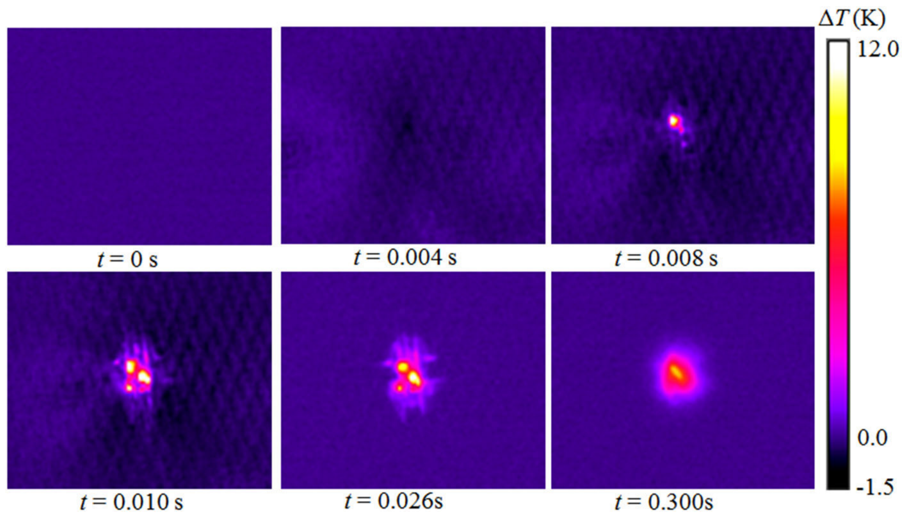

Figure 2. *Images obtained at six time intervals (0, 0.004, 0.008, 0.010, 0.026, and 0.3s) show a CFRP specimen before, during, and after impact (with an energy of 2.8J). The images, obtained using IR thermography, show the effect that the impact has on the specimen's surface temperature. ΔT: Temperature difference in Kelvin, with t=0 used as ambient reference.*

monitoring the color change (i.e., the surface-temperature variation). In particular, a light central zone with yellow/white (i.e., hot) spots develops under the impact.

To obtain more nuanced information about the effects of the impact, we subtract the first image (taken before impact, i.e., for which the specimen surface is at ambient temperature) from each subsequent image in the sequence to create a sequence of ΔT images, i.e., that show the temperature difference over time. Figure 2 shows ΔT images taken at different intervals during the impact (2.8J) on the 1.5mm-thick CFRP panel. As can be seen, the first image is characterized by an almost constant $\Delta T = 0$K value (before load application). At impact ($t = 0.004$s), the surface displays darker zones. These zones, which appear while the specimen is bending under the impact force, correspond to cooling (i.e., the thermoelastic effect). The hot spot (about 12K) that appears at $t = 0.008$s shows material breakage. Later, other hot spots ($t = 0.010$s) appear within the formation of a warm area ($t = 0.026$s), which highlights the fiber orientation and accounts for the extension of delamination. Subsequently, as contact ends and the impactor moves away, the hot zone becomes cooler ($t = 0.300$s) and disappears with time under heat-transfer mechanisms.

Further post-processing of our ΔT images—specifically, extraction of the minima and maxima ΔT values, with a focus on characteristic times[6–8, 10]—may help us to understand more about the impact-damage mechanisms of CFRPs. In particular, information about the peak contact force, the importance of the incurred damage, the location and size of the impact damage, and the overall extension of the impact-affected area can be obtained in a remote and relatively fast way.

In summary, we have used IR thermography to track the behavior of a CFRP specimen in response to the impact damage inflicted by a hammer attached to a Charpy pendulum. Our work highlights the additional data that can be obtained (i.e., on surface-temperature variations and mechanical stresses) by monitoring online impact tests using this approach. In our future work, we intend to study many different material types under a variety of impact energies to obtain a general damage-energy correlation. This information could help developers of new materials to assess their impact performance.

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Simone Boccardi has just completed his PhD course in the Department of Industrial Engineering. His research topic is the application of IR thermography in the investigation of composite materials under bending or impact tests.

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Fabrizio Ricci is an associate professor of aerospace structures. His research interests are in the area of solid mechanics, particularly the behavior of composite structures under static and dynamic loads, with emphasis on wave propagation, ultrasonic NDE, and structural health monitoring.

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References

1. C. Soutis, *Fibre reinforced composite in aircraft construction*, **Prog. Aerosp. Sci. 41**, pp. 143–151, 2005.
2. M. O. W. Richardson and M. J. Wisheart, *Review of low-velocity impact properties of composite materials*, **Compos. Part A: Appl. Sci. Manufac. 27**, pp. 1123–1131, 1996.
3. S. Abrate, *Modeling of impacts on composite structures*, **Compos. Struct. 51**, pp. 129–138, 2001.
4. P. Feraboli and K. T. Kedward, *A new composite structure impact performance assessment program*, **Compos. Sci. Technol. 66**, pp. 1336–1347, 2006.
5. C. Meola and G. M. Carlomagno, *Infrared thermography to impact-driven thermal effects*, **Appl. Phys. A 96**, pp. 759–762, 2009.
6. C. Meola and G. M. Carlomagno, *Impact damage in GFRP: new insights with infrared thermography*, **Compos. Part A: Appl. Sci. Manufac. 41**, pp. 1839–1847, 2010.
7. C. Meola, S. Boccardi, and G. M. Carlomagno, **Infrared Thermography in the Evaluation of Aerospace Composite Materials**, Elsevier & Woodhead Publishing, 2016.
8. S. Boccardi, G. M. Carlomagno, N. D. Boffa, F. Ricci, and C. Meola, *Infrared thermography to locate impact damage in thin and thicker carbon/epoxy panels*, **Polym. Eng. Sci.**, 2017. doi:10.1002/pen.24571
9. https://youtu.be/6ArdqNS6dBQ Video showing the behavior of a carbon-fiber-reinforced polymer sheet under an impact energy of 2.8J. *Credit: C. Meola, S. Boccardi, N. D. Boffa, F. Ricci, and G. M. Carlomagna, Department of Industrial Engineering, University of Naples Federico II*. Accessed 31 July 2017.
10. C. Meola, S. Boccardi, N. D. Boffa, F. Ricci, G. Simeoli, P. Russo, and G. M. Carlomagno, *New perspectives on impact damaging of thermoset- and thermoplastic-matrix composites from thermographic images*, **Compos. Struct. 152**, pp. 746–754, 2016.