Assessment of NDT interferometric techniques for impact damage detection in composite laminates

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Abstract

In this paper, the feasibility of using optical methods to detect impact damage in thin laminates is investigated and discussed. Specimens impacted with different energy levels were analysed by a holographic procedure and by an electronic speckle pattern interferometry technique; the results obtained with the two techniques were compared with those acquired by a pulse-echo full-volume ultrasonic technique.

The investigation showed that both optical methods were able to identify the presence of impact damage, with an efficiency dependent on the through-thickness location of the delaminations produced by impact. The adoption of the ESPI technique allowed significant reductions in inspection times, but quantitative estimates of impact damage were drastically impaired by the high level of speckle noise typical of the technique.

Keywords: Holography; ESPI; D. Ultrasonics; B. Impact behaviour; C. Delamination

1. Introduction

In recent decades, composite materials have found increasing use in structural applications because of their high specific tensile and compressive strengths, and good fatigue and corrosion resistance properties. However, the response of composite structures can be greatly affected by the presence of failure modes such as delaminations, matrix cracks and fibre fracture, which are typical of laminated composite materials [1]. In particular, due to the inherent weakness in the thickness direction of this class of materials, delaminations may develop as a consequence of low-velocity impacts, which inevitably occur during manufacturing, service or maintenance [2,3]. The ensuing growth of delaminations under the action of external loads may degrade the mechanical properties of the structure up to a point where replacement or repair may be necessary to preserve its structural integrity. Efficient damage evaluation techniques are therefore needed for the inspection of components in composite materials in order to ensure a reliable service life, especially in safety-critical structures.

Various non-destructive testing (NDT) methods have been proposed and developed for assessing internal damage in composite laminates; they include vibration techniques, acoustic emission, thermography, X-radiography, eddy currents, ultrasonic inspection and optical techniques [4–9].

Ultrasonics is possibly the most commonly adopted technique for inspection of composite structures, with normal-incidence pulse-echo methods routinely used for detecting and characterizing impact damage in laminates. For example, it has been shown that, with the aid of advanced data acquisition and post-processing proce-
dures, ultrasonic methods can provide a highly detailed three-dimensional image of complex damage states, although, since the acquisition must be conducted on a point-by-point basis, damage detection can be time-consuming, particularly for large components [10].

Among the above-mentioned techniques, non-conventional inspection methods based on holography have demonstrated great potential in revealing delaminations in composites [11–15]. These techniques, which are based on the ability of holographic interferometry to measure out-of-plane displacements with high sensitivity, are non-contacting and make it possible to perform full-field analyses on the surface of complex geometry components. The efficiency of holographic procedures depends however on many parameters, such as the characteristics of the material, the nature of the defects and the method of inducing the out-of-plane displacements necessary to identify internal damage.

A different optical method, the Electronic Speckle Pattern Interferometry (ESPI) technique [16], has also been applied for damage detection in composite laminates. This technique is advantageous for non-destructive inspection [17,18] because, unlike holography, it does not require wet processing. The fringe patterns are digitally displayed in real time, thus speeding up the testing procedure.

In this study, both holographic and ESPI procedures were developed and investigated with the aim of characterizing these methods for the detection and identification of impact damage in composite laminates. The results obtained with the two techniques by examining specimens with various impact damage patterns are discussed and compared with the detailed damage pictures reconstructed as a reference by pulse-echo full-volume ultrasonics.

2. Experimental details

2.1. Materials and impact tests

Quasi-isotropic laminates of two composite materials were examined in this study. The first material was graphite/PEEK with 63% by volume of AS4 fibres, chosen because it is representative of the class of tough thermoplastic composites. The second material system consisted of graphite Grafil 6KXAS fibres in Fibredux 914 epoxy resin, with 60% fibre volume fraction. The stacking sequences were [0/(±45/90)]2s for graphite/PEEK laminates (thickness = 2.2 mm) and [(±45/0)/90]2s for graphite/epoxy laminates (thickness = 2.0 mm).

Impact tests were performed on a drop-weight impact-testing machine, with specimens clamped between two rings of 70 mm internal diameter. The impactor, with a total mass of 2.28 kg, was instrumented with a semiconductor strain-gauge full bridge bonded to the hemispherical tup (12.5 mm in diameter) for contact force measurement. Impact and rebound velocities were measured by an infrared sensor and thus allowed us to perform a dynamic calibration of the load sensor by using the Impulse-Momentum equation [19]. The energy absorbed by the specimen during impact was obtained as a function of time by integration of the contact force-signal.

In order to achieve different levels of damage, impact energy was varied over the range 1.35–8.3 J by changing the drop height of the impactor mass; the corresponding impact velocities ranged between 1.09 and 2.70 m/s.

2.2. Optical non-destructive testing

The Holographic Non-Destructive Testing (HNDT) method is based on the application of the holographic interferometry technique for the detection of local defects. Holographic interferometry [20] can be defined as the interferometric comparison of two or more waves, at least one of which is holographically reconstructed. This full-field technique is particularly suitable for measuring out-of-plane displacements by the analysis of interferometric fringe patterns, with sensitivity of the order of half the wavelength of the laser light used.

In HNDT applications, damage zones are identified as anomalies in the surface out-of-plane displacements – and thus in the fringe patterns – induced by the application of a small load to the component under inspection. Although holographic interferometry measures surface displacements, both superficial and internal flaws can be detected as long as their presence affects the surface displacement field.

Various methods have been proposed to apply the required load to the inspected component, including mechanical and thermal loading, vacuum or pressure application and vibrational excitation [12,14,15]. While the most suitable method and test procedures depend on the characteristics of the component and on the nature of the damage, a common precaution involves preventing rigid body motions of the test object during load application.

A preliminary investigation conducted during our experiments showed that a thermal load applied by lightly heating the impacted specimens with an infrared lamp was an effective method for identifying impact damage in the samples. During the tests, specimens were rigidly fixed to a support to minimise rigid motions and all the equipment used was arranged on an optical table in order to reduce the effects of environmental vibrations. The thermal stress was obtained with a 250 W infrared lamp set about 10 cm from the rear surface of the sample. The source of coherent light used was a He–Ne continuous laser of 35 mW power. A diagram of the experimental set-up is shown in Fig. 1.
The tests were carried out using the double-exposure technique, where two holograms, relative to the object in undeformed and deformed conditions, respectively, are superimposed on the same holographic plate.

In the adopted procedure, a hologram of one side of the specimen is done first; then, the thermal load is applied by heating the rear side of the specimen for a period of about 30 s. After about 5 min, the second hologram is recorded on the holographic plate. Finally, the fringe patterns are digitized with a CCD camera connected to a personal computer.

The Electronic Speckle Pattern Interferometry technique [16] with out-of-plane sensitivity was also investigated during the study. This technique is based on the coherent combination of speckle fields and on the use of digital systems to obtain the interference fringes. The arrangement of the experimental set-up is similar to that of the holographic technique and the fringe patterns are obtained in real time with the use of a CCD camera connected to a personal computer.

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The required acquisition time for a typical ultrasonic scan (as defined by a database consisting of a bi-dimensional array of around 10^5 ultrasonic waves, with each wave defined by 512 data points) is about 45 min.

3. Results and discussion

The fringe patterns obtained with the HNDT technique on the impact side of two graphite/PEEK samples characterized by an absorbed energy of 1.44 and 1.9 J are shown in Figs. 2 and 3, respectively. Figs. 2 and 3 show an enlarged portion of the recorded interferograms, which were relative to the whole surface of the specimens, in order to highlight the damaged areas. As can be seen in the interferograms, the presence of internal damage in laminates is revealed by concentric fringes indicative of anomalous out-of-plane displacements occurring on the surface of damaged panels.

Fig. 4 shows the delamination map obtained by ultrasonics for the absorbed energy level of 1.9 J. From this map, where the grey levels indicate different delamination depths, we can observe that, while the total projected delamination area is approximately circular with
the centre at the impact point, the three-dimensional damage pattern is characterized by a typical spiral staircase shape, with delaminations mainly occurring on the intermediate interfaces of the laminate.

To investigate the sensitivity of the interferometric method, the digitized images of the fringe patterns were processed by image analysis software to obtain an estimate of the damage area. Since the closed-fringe pattern is directly associated with the presence of delaminations, the size of the total projected delamination area was estimated by contouring the largest fringe around the impacted zone and measuring the enclosed area, following the approach proposed in [14].

Fig. 5 compares the total delamination area estimated by the HNDT method with the projected delamination areas obtained at different depths by full-volume ultrasonics. We can observe that the total projected delamination area measured by ultrasonics (which coincides with the projected delamination area at a depth of 2.2 mm, corresponding to the total thickness of the specimen) is much larger than the delamination area evaluated by holography. In particular, Fig. 5 shows that the holographic technique does not appear to be sensitive to the presence of delaminations lying at interfaces more than about 0.7–0.8 mm away from the impact side; this is because of the small influence exerted by deep delaminations on the surface displacement field.

It is worth noting that since the main delaminations occurred at the intermediate interfaces of the laminates, similar interferograms and damage area estimates were obtained with the HNDT technique by inspecting the non-impact face of the laminate.

Fig. 6 depicts the fringes obtained on the impact side of a graphite/epoxy sample characterized by an absorbed energy of 6.25 J. As can be observed in the figure, the presence of impact damage is again identified by a fringe pattern (with a shape similar to that of the graphite/PEEK samples) associated with the local gradient of the out-of-plane displacements field induced by delaminations.

However, ultrasonic C-scans reveal that the extent and through-thickness distribution of delaminations in graphite/epoxy samples are quite different from that previously described for graphite/PEEK laminates. The ultrasonic map of Fig. 7 (relative to the graphite/epoxy specimen of Fig. 6) shows that delamination sizes tend to increase on moving from the impacted side to the rear side, with the largest delamination occurring at the +45°/−45° interface close to the non-impact side. The presence of this delamination (about 1.9 mm far from the illuminated face) is not detected by the HNDT technique, as can be seen in the interferogram of Fig. 6.

Like the indications deduced from the analyses on graphite/PEEK samples, these results seem to indicate that delaminations away from the inspection face do not make a significant contribution to the out-of-plane
displacement of the observed surface. This is probably a consequence of the high rigidity of the sublaminate between the flaw and the inspected face.

To confirm this hypothesis, interferograms were taken of the non-impact side of the specimen. Fig. 8 shows that, in this case, the fringe pattern depicting the out-of-plane displacements did reveal with reasonable accuracy the shape and extent (as visible in the direct comparison of Fig. 9) of the delaminations at the +45°/−45° interface, now very close (about 0.1 mm) to, and thus greatly affecting the displacement field of, the inspected side.

All the impacted samples examined by holography were also inspected by the ESPI technique, which, unlike HNDT, is a real-time procedure, thus enabling us to achieve significant reductions in the time needed to perform tests.
As an example, Fig. 10 shows the interferogram obtained for the graphite/PEEK panels of Figs. 3 and 4 (absorbed energy = 1.9 J). As seen in the figure, the ESPI technique is capable of identifying impact damage location, although the fringe patterns suffer from large speckle noise. In fact, since the speckle effect is produced by the random scattering of laser light from optically rough surfaces, the fringe patterns which represent the out-of-plane displacement fields are intrinsically embedded in noise. The low readability of ESPI fringe patterns drastically limited the accuracy in quantification and characterization of damage areas and translated into lower sensitivity to internal damage as compared to HNDT.

As previously discussed, fringes with improved signal-to-noise ratio could be produced by introducing into the ESPI set-up a phase-shifting device to recover the phase maps from the recorded intensities. However, this procedure requires more computation time with respect to the intensity fringe approach applied in this study.

4. Conclusions

An experimental study was conducted to investigate the use of HNDT and ESPI techniques for impact damage detection in composite laminates.

It was observed that both optical techniques were able to identify the presence of impact damage in thin laminates; because of its low signal-to-noise ratio, the ESPI technique was, however, characterized by lower sensitivity than HNDT.

The results obtained with the HNDT method showed a good quantitative correlation with those derived from full-volume ultrasonic C-scans as far as the detection of shallow delamination was concerned; on the contrary, the holographic technique appeared to be inadequate for detecting and quantifying delaminations some distance from the inspection side.

In conclusion, the experimental analysis indicated that the optical NDT techniques prove to be useful for a fast preliminary examination of structural components subjected to impact. Full-field measurements yielded by these methods may provide valuable information for guiding a more detailed examination of impact damage by complementary techniques.

References