DETECTING BARELY-VISIBLE IMPACT DAMAGE IN COMPOSITES USING FULL-FIELD SLOPE MEASUREMENTS

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1 Introduction

As small impacts may have a large influence on the mechanical behaviour of a composite structure, it is therefore very important to be able to detect and characterize damage to predict the part's remaining life. A large amount of work has been already done in damage detection using different measurement techniques such as C-scans [1], thermography [2], shearography [2], holography [1], digital correlation [3] and thermoelasticity [4]. The novelty of this work is to broaden the choice of non-destructive evaluation (NDE) techniques for damage detection in layered composite materials.

A special configuration of the grid method, deflectometry, has been used to retrieve strains without any smoothing. The grid method has been already used as a NDE technique with the in-plane configuration, as in [5] and with the deflectometry to extract stiffnesses of samples with stiffness reductions, as in [6]. This work uses the deflectometry method on a cantilever beam in bending. In the first part, the samples are presented, and then the measurement technique is detailed, followed by the finite element (FE) models, finishing with the results and discussion.

2 Samples

The samples have been manufactured using a carbon/epoxy pre-impregnated composite material (Hexcel IM7-8552) in a 32 plies quasi-isotropic lay-up [0 45 -45 90]4s. Their dimensions are 250 mm long (300 mm in fact, but 50 mm reserved for the clamp), 50 mm wide and 4 mm thick.

Five types of sample have been manufactured: the undamaged case which will be used as a reference, a case with a 50mm-long single delamination in the mid-plane, centred longitudinally and across the full width. The delamination has been realized experimentally using a single film of PTFE (25 µm thick). After the first tests, it has been noticed that the film was bonded to the resin, therefore the delaminations have been opened using a blade. A third case contains 7 full width delaminations equally spaced through the thickness (every 0.5 mm), increasing in length towards the back surface, from 25 mm to 55 mm. As the single film did not successfully replicate a delamination, two layers of a thinner film for each delamination have also been tried but opening is still required. Two impacted cases have been considered too. The samples were clamped between two steel plates, both of them containing a 40 mm diameter cut-out. It allowed the impactor to hit the sample and the sample to deform underneath. The first is an impact with a 15 mm radius impact tup at 15 J (5.3 kg mass dropped from 0.28 m, impact velocity 2.36 m/s) and the second has been impacted with a 50 mm radius tup at 25 J (5.63 kg mass dropped from 0.45 m, impact velocity 2.96 m/s). An ultrasonic probe was used to check that delaminations have been induced in the sample by the impact.

3 Deflectometry

The method consists of observing the reflection of a grid on the surface of the specimen. A general view of the set-up is presented in Fig. 1. As composite components do not have enough specular reflection, a resin (Sicomin Surf Clear) opacified with a filler (Graphite powder from Sicomin) is applied to make a thin reflective coating. A first picture is taken before loading and a second is taken when the load is applied. Therefore, the camera observes a deformation of the grid and these deformations are only affected by the loading and not by misalignments for instance. The pictures at rest and under loading will be evaluated using spatial phase stepping (windowed discrete Fourier transform algorithm) for each direction. The phase at rest will be subtracted from the phase maps in the loaded state to obtain the phase modification introduced only by the loading. As these two phase maps are wrapped, an unwrapping process is done using a routine developed by Bioucas-Dias and Valadao [7]. Then these maps are divided by the sensitivity to correctly scale them, as in [6]. To obtain the curvatures, the slopes are differentiated using a simple point-to-point finite difference differentiation algorithm with no smoothing. The curvatures are multiplied by half the thickness to obtain the strains, based on the thin plate theory. The final measurements are true strains only where no delaminations are present. In the delaminated region, the Love-Kirchhoff assumption, linearity of the displacements through the thickness, is not respected anymore, this is why they will be referred to as “equivalent strains”. It is worth noting that the measured quantity is independent of any dent created during the impact as the surface has been covered by an opaque resin and it is the slope of the flat surface that is measured.

4 Finite element model

The corresponding FE models have been created using 3D quadratic bricks (C3D20 in Abaqus/Standard) with dimensions 1 mm long and wide and 0.125 mm thick. Therefore each layer of elements through the thickness represents a single ply of composite and they have the unidirectional material properties and an orientation. At the root, all the nodes have been clamped and a 5 N point load has been introduced at the centre of the free edge. The analysis is static with small displacements. The delaminations have been inserted by disconnecting the nodes in the delaminated area and frictionless surface contact interaction was used to prevent any inter-element penetration at delaminations. As the experiments provide curvatures from slopes, it is therefore better to process the numerical results in the same way to make a comparison. The out-of-plane displacements have been output for the nodes on the compressive surface, they have then been differentiated twice to obtain the curvatures and multiplied by half the thickness to obtain the so-called "equivalent strains". For the impacted samples, as a first approach, an annulus of delaminations with the radii corresponding to the damage visible in the CT-scans has been included. It must be noted that the FE models are not completely representative of the real damage so it is possible that the FE results may over-estimate the damage.

5 Results

Fig. 2-4 present the equivalent strains for all samples coming from the experiments and the FE simulations. They all represent equivalent strains and are plotted in microstrains. Fig. 2a, 3a and 4a present the results for the undamaged sample coming from the FE simulations and the experiments. There is a good general agreement between the measurements and the numerical results. But a small mismatch is visible in the clamp region, lower part of the figures, which is normal as clamping is a very difficult boundary condition to create experimentally. On the top edge, the mark visible in the equivalent transverse strains, Fig. 3a, is the local transverse strain induced by the point load and it is also visible as a local sign change in the equivalent shear strains, Fig 4a. It must be noted that the resolution of ± 2 μm/m reached here is quite remarkable. Fig 4a which is a map of 63 by 313 data points, presents some effects that are in the order of a couple of microstrains for a global colour scale of 20 μm/m. As previously stated, these results have been obtained without using any smoothing.

Fig 2b, 3b and 4b present the results from the FE simulation and the experiments for the sample with the 50 mm long delamination. From Fig 2bi, the effect of a single delamination is quite noticeable and is clearly seen in the experiments. As mentioned previously, there have been some issues with the manufacturing of artificial delaminations, so it is quite possible that the film is still bonded to the resin in some places, explaining why the effect for the equivalent longitudinal strains is less marked in the experiments than in the numerical results.

The equivalent strain maps for the sample with seven delaminations through the thickness are presented in Fig 2c, 3c and 4c. Because the effect in the longitudinal strain fields is much larger, a different scale is used in Fig 2c, the blue represents -600 μm/m and the red +500 μm/m. Fig 3c and 4c use the standard colour scale. Although the results are somewhat different from what the FE simulation predicted, a small effect is noticeable in the experiments. The difference can be explained by the fact that the “delaminations” are not in fact fully delaminated.

The equivalent strain maps for the sample impacted with the 15 mm radius tup at 15 J are presented in Fig 2d, 3d and 4d. It must be emphasised that the measured curvatures are not related to the dent created during the impact, as the sample has been coated. If one scans Fig 2di from bottom to top, one can find the same alternation, and lower/upper values to what is present in Fig 2bi. The pattern from the experiments, Fig 2dii, is also visible in the FE results even though it is less distinct in the measurements. As noted previously, the numerical model is not a perfect representation of the experimental sample. This shows that the pattern in the equivalent longitudinal strains from a single delaminated sample is also visible in the more complex case, the impacted sample.

The equivalent strain maps for the sample impacted with the 50 mm radius tup at 25 J are presented in Fig 2e, 3e and 4e. It is noticeable that the effect of the impact is less marked in this sample because the radius of the impactor tup is bigger. Also from the maps, it is possible to state that the impact was not located exactly in the middle of the beam but slightly offset to the right on the top.

Conclusion

A method has been presented to detect damage in composite materials from surface slope measurements. It was able to reveal the location and extent of quite small damage, for instance 30 mm long central delaminations or 15 J impacted samples. For the artificially delaminated samples, the measurement technique did not give the same results as the FE models mainly because of issues with the experimental delaminations. Creating an artificial delamination is a problem reported in several papers and even a standard [8] was proposed for it but so far it is not possible to create a representative delamination without some mechanical straining after cure. The impacted samples were a very nice illustration of what the literature describes about barely visible impact damage and they also pointed out that the FE models need to be modified to obtain a better correlation. The technique proved to be very sensitive, a resolution of about 2 μm/m over a map of 63 by 313 data points was achieved. This is a nice feature of this reflection technique. It should be noted that similar data processing would be possible with a random speckle pattern (reflection DIC). Another advantage of looking at strain maps instead of displacements is the existence of 3 maps for each measurement, each of these maps representing a different behaviour affected by different stiffnesses. In future work, some attention will be brought to the FE model, in particular to introduce more realistic delamination patterns according to finer CT-scans. Also this work will be extended to plates, giving a more complex structure to study.

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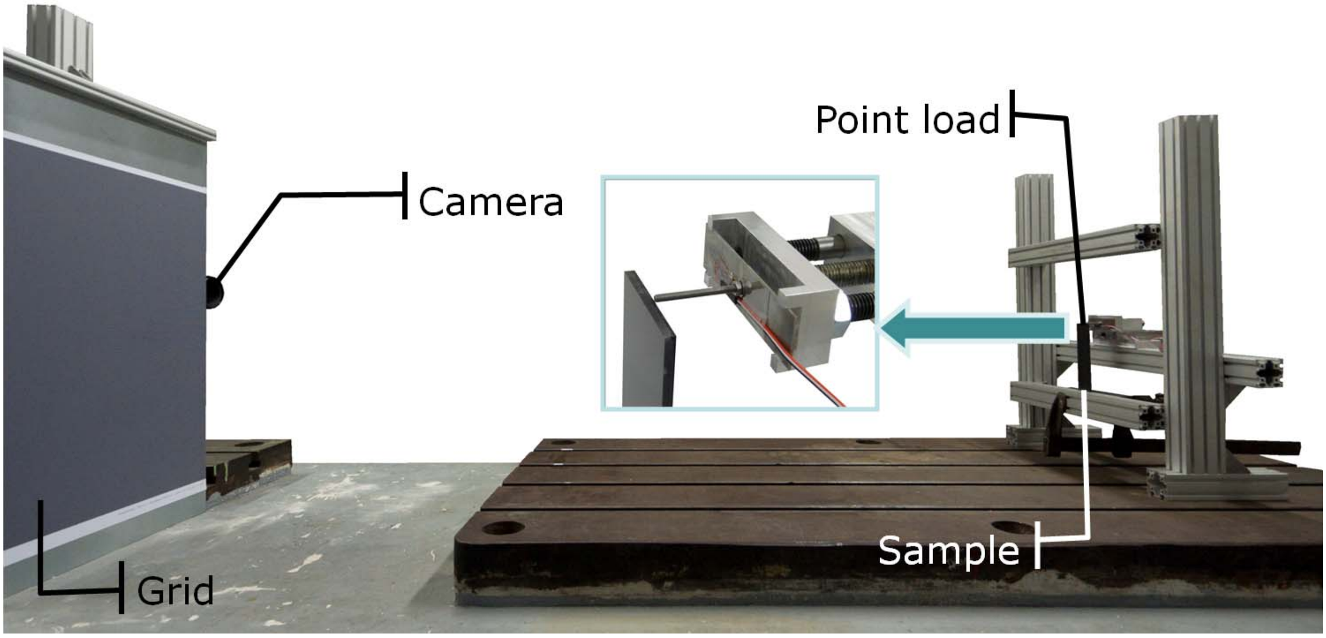
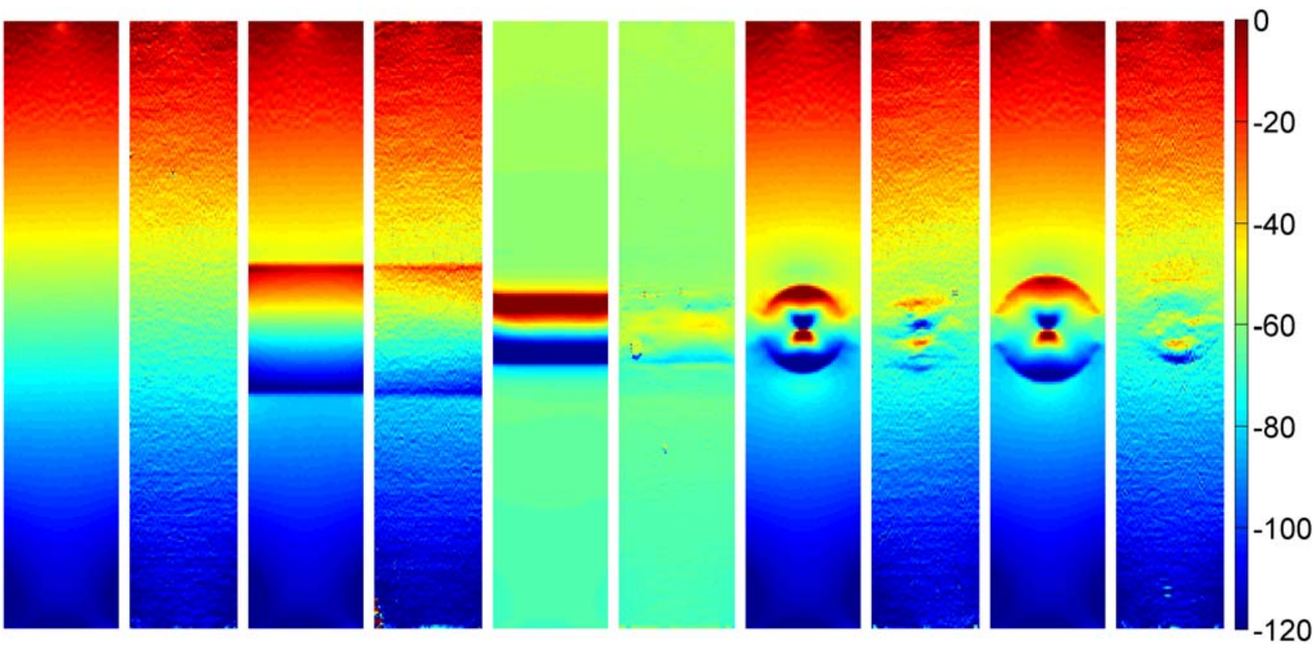


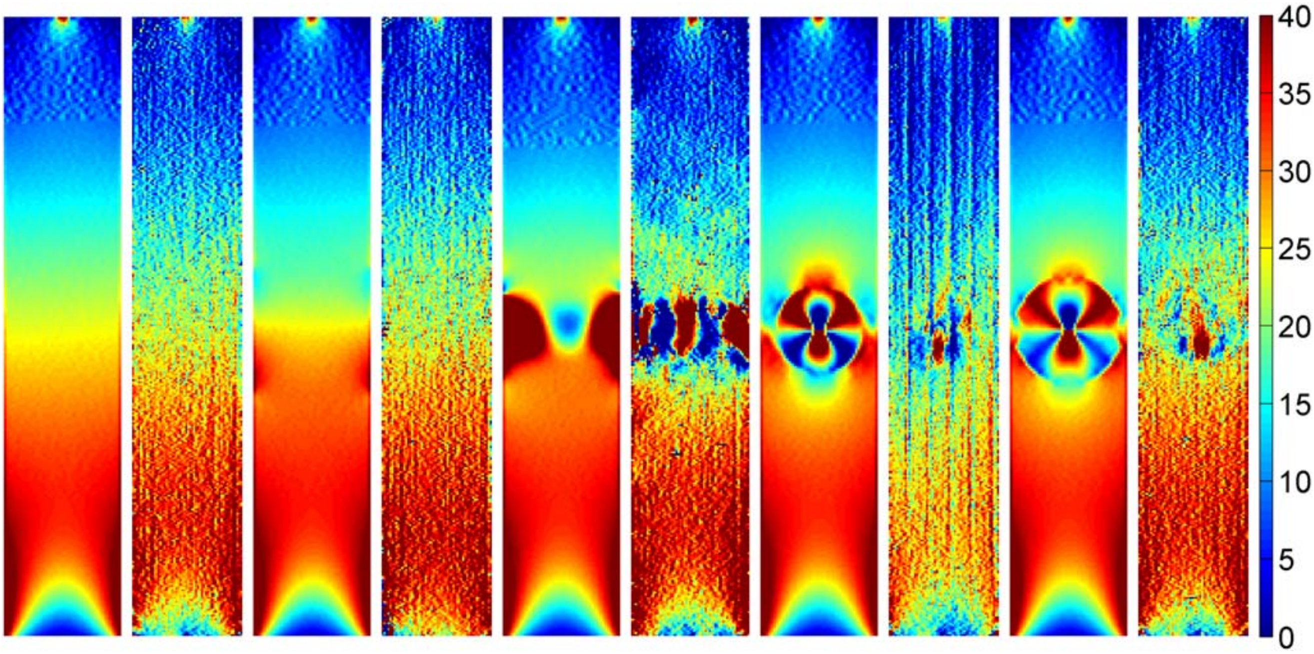
Figure 1: General view of the set-up



(i) FE (ii) Exp (i) FE (ii) Exp (i) FE (ii) Exp (i) FE (ii) Exp (i) FE (ii) Exp

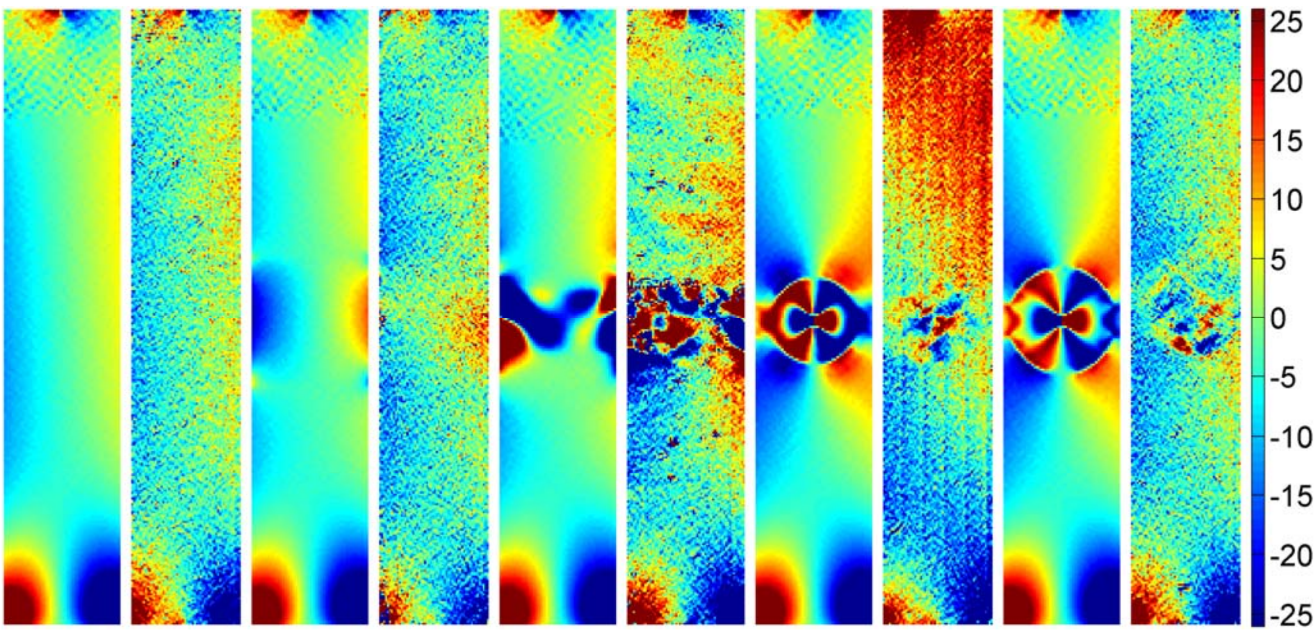
(a) Undamaged (b) 50 mm long (c) 7 delaminations (d) 15 mm radius (e) 15 mm radius

Fig. 2: Equivalent longitudinal strain fields, represented in microstrains. “FE” is for results coming from simulations and “Exp” for experimental results. In Fig 2c, the blue represents -600 µm/m and the red +500 µm/m.



(i) FE (ii) Exp (i) FE (ii) Exp (i) FE (ii) Exp (i) FE (ii) Exp (i) FE (ii) Exp
(a) Undamaged (b) 50 mm long (c) 7 delaminations (d) 15 mm radius (e) 15 mm radius

Fig. 3: Equivalent transverse strain fields, represented in microstrains. “FE” is for results coming from simulations and “exp” for experimental results.



(i) FE (ii) Exp (i) FE (ii) Exp (i) FE (ii) Exp (i) FE (ii) Exp (i) FE (ii) Exp
(a) Undamaged (b) 50 mm long (c) 7 delaminations (d) 15 mm radius (e) 15 mm radius

Fig. 4: Equivalent twist strain fields, represented in microstrains. “FE” is for results coming from simulations and “exp” for experimental results.