STRUCTURAL RESPONSE AND DAMAGE RESISTANCE OF SANDWICH COMPOSITES SUBJECTED TO LOW VELOCITY IMPACT

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Abstract

The results of an investigation into the low-velocity impact response of sandwich composites are reported in the paper. Impact tests were first conducted to examine the type and extent of the damage occurring in various configurations of sandwich panels with carbon/epoxy skins and PVC foam core. Experimental data were then used to evaluate the predictive capabilities of an FE tool recently developed by the authors to model impact damage in sandwich composites.

1. Introduction

Sandwich panels consisting of composite skins bonded to a low-density core material are increasingly used as lightweight primary structures in many wind energy, aerospace and marine applications because of their high bending stiffness, good static, fatigue and buckling strength, and excellent corrosion resistance. As an example, composite sandwich structures are nowadays widely used in many parts of modern wind turbine blades, such as the aeroshells and the webs of the main spar, and are also under consideration for possible replacement of monolithic composites in other portions of blades [1].

One of the main limitations of sandwich composites is their high susceptibility to impact-induced damage [2], which may result in significant strength reduction, even when the damage is undetectable by visual inspection. Detailed understanding and reliable predictions of the extent and nature of impact damage likely to occur during service is thus required for a safe estimation of the life and residual properties of a sandwich structure.

The impact behaviour of a variety of sandwich configurations with carbon/epoxy facings and PVC foam cores was investigated in this study. The structural response of the sandwich panels was characterized by the analysis of data acquired during instrumented drop-weight impact tests. The damage induced by impact was reconstructed by combining information collected through both non-destructive and destructive inspection techniques. The experimental results were finally used to assess the predictive accuracy of an FE model recently developed by the authors to simulate impact damage in sandwich composites.

2. Experimental procedures

Sandwich panels with carbon/epoxy laminated skins and PVC foam core were investigated in this study. Six different panel configurations, consisting of two skin layups and three core densities, were manufactured, tested and examined for damage.

The laminated skins were made of unidirectional prepreg layers (Seal Texipreg® HS300/ET223, suitable for vacuum-bag-only processing at curing temperatures ranging between 85°C and 125°C) laid up according to two lamination sequences (a 5 layer cross-ply $[0/90_3/0]$ layup and a 10 layer $[0_3/\pm45]$s layup). Individual plies had a fibre volume ratio of 0.62 and a nominal thickness of 0.32 mm.

The core material was a closed cell PVC foam (DIAB Divinycell® HP). Divinycell HP is an elevated temperature foam, specifically developed for use in combination with low to medium temperature prepreg systems. Panels with three foam core densities (HP60, HP100 and HP160, with densities of 65, 100 and 160 kg/m^3, respectively) were manufactured for the experiments. All sandwich configurations had a core thickness of 10 mm.

Sandwich plates 250 x 250 mm^2 in size were vacuum-bagged and consolidated using a co-curing process, during which the prepreg layers were simultaneously cured and bonded to the core without the use of additional adhesive material. The curing cycle consisted of a 3°C/min heating stage, followed by a 6 h dwell at 100°C and a cooling stage to room temperature maintaining vacuum.

Impact tests were conducted using an instrumented drop-weight testing machine equipped with a 2.34 kg impactor supplied with a hemispherically ended rod of 12.5 mm in diameter. The panels were subjected to impact with energies ranging between approximately 1 J and 9 J, obtained by varying the drop height of the impactor.

The internal damage occurring in the impacted composite skin was generally assessed by penetrant-enhanced X-radiography. In selected sandwich plates the through-thickness distribution of damage was also qualitatively reconstructed by stereoscopic X-radiography, ultrasonic C-scanning and optical microscopy of polished cross-sections.

3. Experimental results

3.1. $[0/90_3/0]$ sandwich composites

Fig. 1 shows representative force-time histories and force versus displacement plots for sandwich composites with $[0/90_3/0]$ skins and HP60, HP100 or HP160 foam core impacted with an energy of about 6.3 J. The plots show that the density of the core has a significant effect on the structural response of the sandwich plates under impact. As an example, the load-time histories of Fig. 1 show that the maximum force increases of about 25% when the core density is increased from 65 kg/m^3 (HP60 foam) to 160 kg/m^3 (HP160 foam). The effect of the core density is also evident in the force-displacement curves, which show that sandwich composites with higher density cores exhibit stiffer responses than those of panels with lower foam density. Despite some oscillations and fluctuations in the force signal, which can be related to dynamic effects in the plate-impactor system, we may identify two distinct stages of the force-displacement curves. The first stage is characterized by an approximately linear behaviour up to a knee point at a load level of about 1 kN; above this knee point the curves exhibit a clear drop in stiffness, which is associated to damage and degradation phenomena occurring both in the core and in the top facesheet during the impact event. A nonlinear stiffening effect is also observed under increasing displacements on the second stage of the force-displacement traces.

Impact curves with similar trends were reported in other studies on the indentation or low-velocity impact response of composite sandwich structures [3]. As visible in the plots of Fig. 1, both the stiffness drop following the knee point and the stiffening effect at large displacements appear more prononunced in sandwich panels with lower core density; this suggests that nonlinearities or damage events occurring in the core may play a more significant role in low-density than in high-density foam sandwich composites.

The graph of Fig. 2 plots the projected damage area (as measured on X-radiographs) for [0/90$_3$/0] sandwich composites with different core densities; typical X-ray pictures of damage induced by impact in HP60 and HP160-based sandwich composites are presented in Fig. 3. It is seen that, despite the strong influence of core density on the structural impact response of sandwich panels, both the planar damage extent and the nature of failure modes occurring in the laminated skins are not greatly affected by the density of the core material. For all core densities, initial damage in the impacted skin consists of tensile matrix cracks developing in the 0° layer opposite the impact side, and of shear matrix cracking occurring in the middle 90° layers. With increasing loads, tensile and shear matrix cracks trigger the initiation of a two-lobe delamination on the lowermost 90°/0° interface, which is then followed by a smaller delamination on the uppermost 0°/90° interface. No significant fibre damage was detected in the impacted facings for the entire range of impact energies investigated.

3.2. [0$_3$/±45]s sandwich composites

Figure 4 shows representative load histories and force-displacement curves measured during 6.3 J impacts on sandwich composites with [0$_3$/±45]s facings and three core densities (65, 100 and 160 kg/m^3). We may see that the structural response to impact of [0$_3$/±45]s sandwich composites is also controlled by the properties of the core, with a clear increase in the maximum contact force and in the slope of the force-displacement curves with increasing foam density. Similarly to what observed for [0/90$_3$/0] panels, the force–displacement curves are approximately linear up to a knee point (occurring in this case at a load level higher than 2 kN), beyond which the curves clearly exhibit a significant decrease in slope.

The X-radiographs of Fig. 5 show typical damage induced by 6.3 J impacts on the composite skins of [0$_3$/±45]s sandwich panels based on HP60 and HP160 cores. The analysis of X-ray pictures taken over the whole examined range of impact energies shows that, for all core densities, damage initiates at an impact energy level of about 1 J with a large bending matrix crack developing in the lower 0° layers, followed by delamination at the -45°/+45° interface and matrix cracks in the 45° plies. With increasing impact energies, delaminations initiate and grow at all remaining interfaces in association with matrix cracking in adjacent layers. Fibre fracture is also visible in the top 0° layers for impact energies higher than about 6 J.

Even though the nature of the main damage mechanisms does not appear to be affected by the density of the core, the X-rays of Fig. 5 show that sandwich panels with low core density (HP60) have larger projected delamination areas than sandwich panels with high core density (HP160). This effect is readily apparent in the graph of Fig. 6 which shows that the use of higher density foam in the core of [0$_3$/±45]s sandwich composites results in smaller planar damage areas over the entire range of impact energies investigated. A similar effect was also observed and described in recent studies for different material systems [4,5].

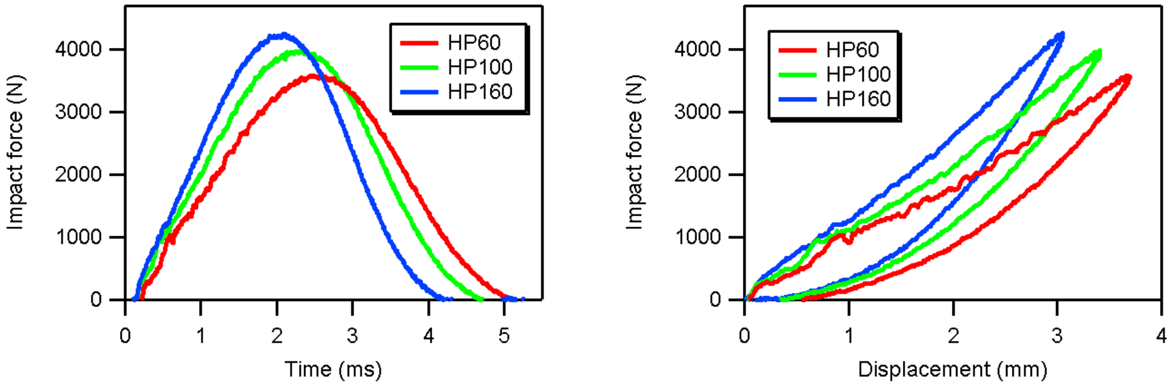

Fig. 1: Force-time histories (left) and force versus displacement curves (right) for sandwich composites with [0/90$_3$/0] skins and HP60, HP100, and HP160 foam core. Impact energy = 6.3 J

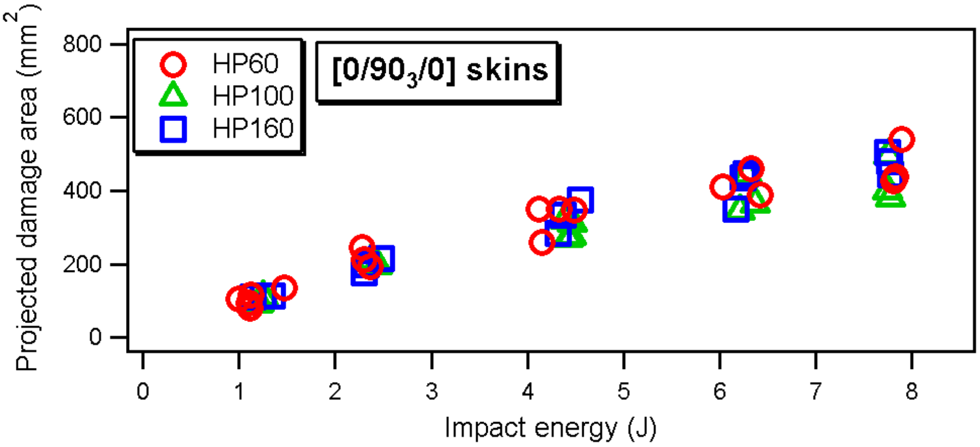

Fig. 2: Projected damage area for sandwich plates with [0/90$_3$/0] skins and different core densities.

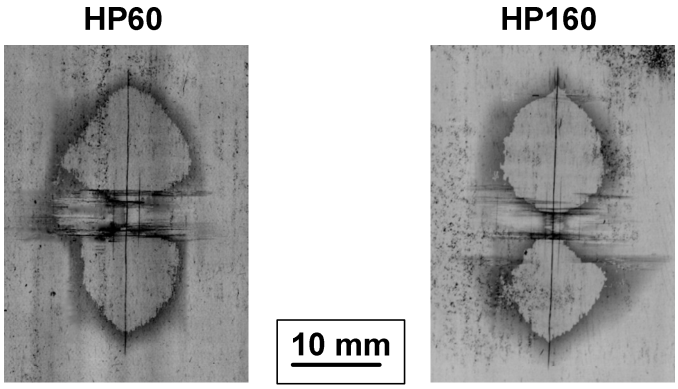

Fig. 3: X-radiographs of damage induced by a 6.3 J impact on sandwich composites with [0/90$_3$/0] skins and HP60 (left) and HP160 (right) foam core.

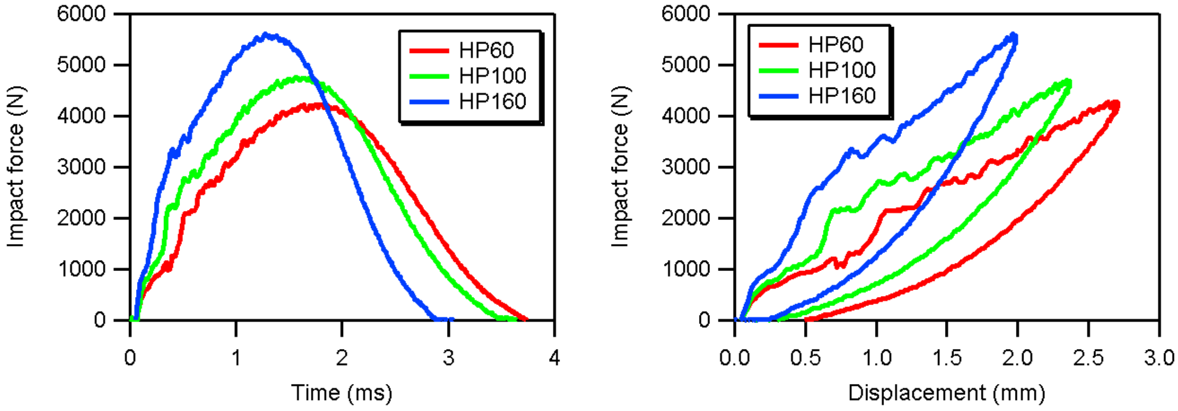

Fig. 4: Force-time histories and force versus displacement curves for sandwich composites with [0_3/±45]s skins and HP60, HP100, and HP160 foam core. Impact energy = 6.3 J

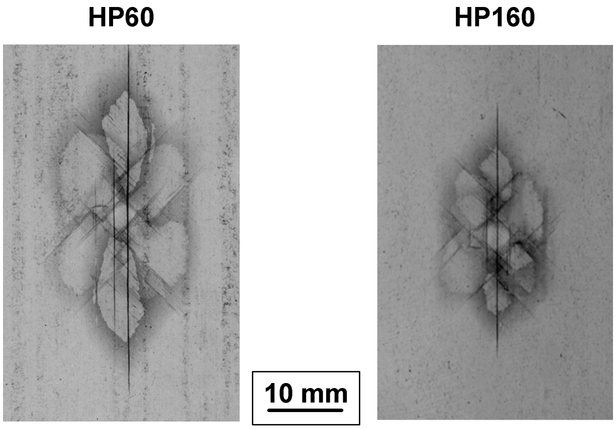

Fig. 5: X-radiographs of damage induced by a 6.3 J impact for sandwich composites with [0_3/±45]s skins and HP60 (left) and HP160 (right) foam core.

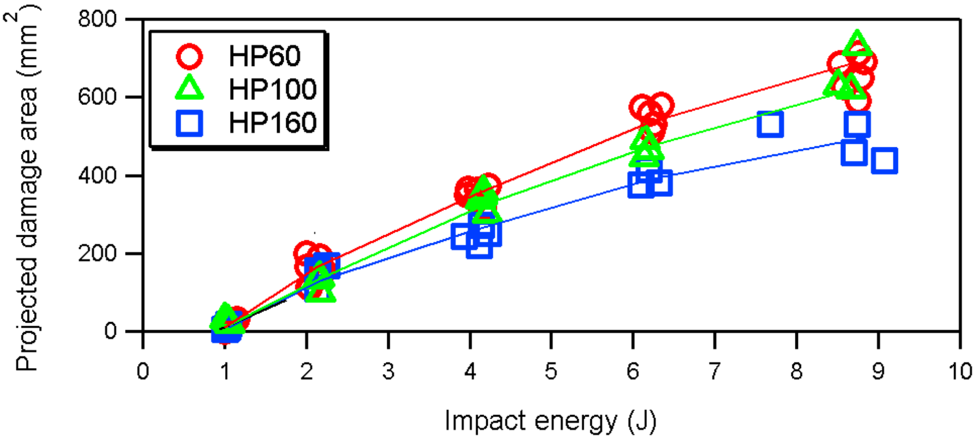

Fig. 6: Projected damage area for sandwich plates with [0_3/±45]s skins and different core densities.

4. Numerical simulations

The results of the experimental analyses were used to assess and validate the predictive capabilities of an FE model recently developed by the authors to simulate the response to impact of sandwich composites. Progressive damage models based on the use of continuum damage mechanics and interfacial cohesive strategies were employed to predict the major intralaminar and interlaminar degradation modes occurring in the impacted facesheets. A crushable foam plasticity model was adopted to reproduce the plastic behaviour of the foam cores. Details on the FE model may be found in [6].

The graphs of Fig. 7 compare the force-displacements traces predicted by FE analyses with experimental curves obtained for impact energies of approximately 6.3 J. It may be seen that a good agreement is achieved between experiments and simulations for the different sandwich configurations. In particular, the FE model correctly reproduces the stiffer response and the higher peak load of sandwich panels with higher density core. Furthermore, the numerical simulations are capable of predicting the characteristic nonlinearities, including the significant stiffness change occurring at the knee of the curve, typical of the impact response of the panels.

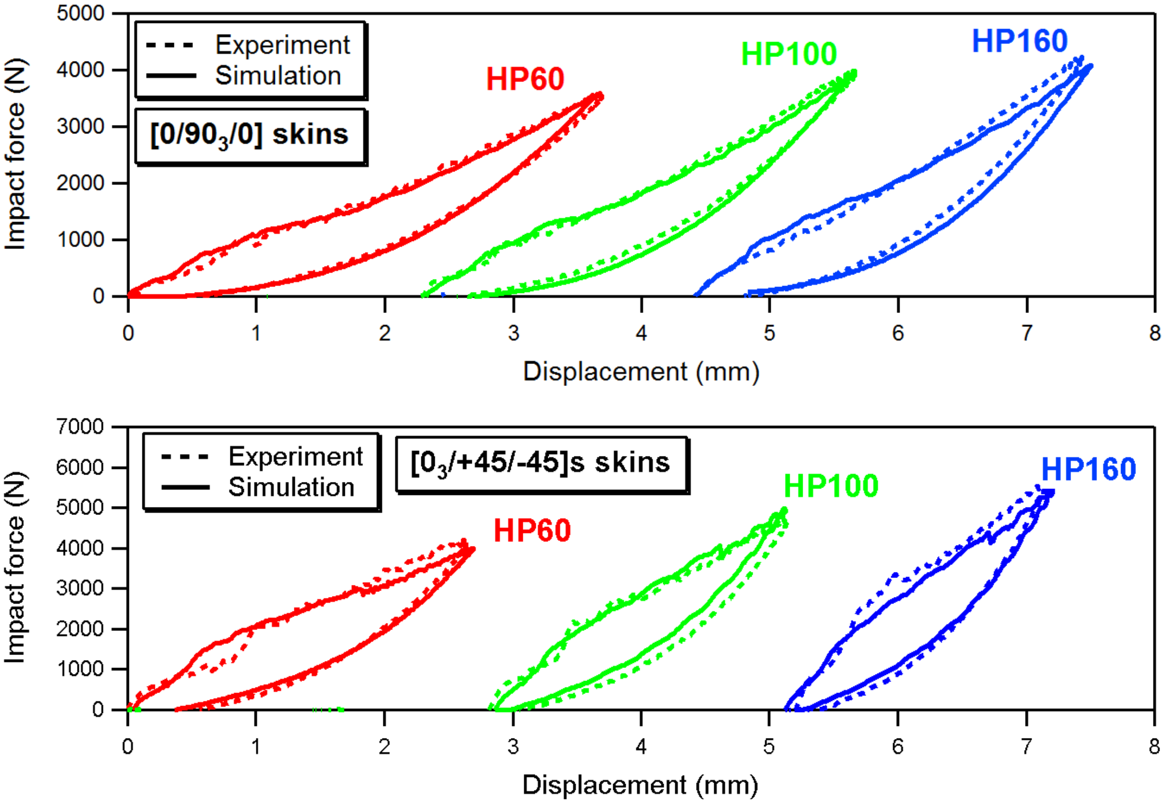

Fig. 7: Comparison between predicted and experimental force-displacement curves for sandwich plates with [0/90$_3$/0] (top) and [0$_3$/±45]s (bottom) skins and different core densities. Impact energy ≈ 6.3 J

Comparisons between experiments and simulations in terms of projected damage area and individual delaminations occurring in the composite skins of sandwich panels with two core densities are illustrated in Figs. 8-10. The graphs of Fig. 8 plot experimental and predicted values of projected damage areas for sandwich panels with HP60 and HP160 core. Images of delaminated areas as reconstructed by ultrasonic C-scanning and obtained by FE simulations (where different colours correspond to different delamination depths) are compared in Figs. 9 and 10. The results presented in Figs. 8-10 show that the FE model predicts with good accuracy the global planar damage size and reproduces the characteristic three dimensional damage patterns developing under impact in the different sandwich configurations. As an example, the model correctly simulates the decrease of damage size with increase of core density in [0$_3$/±45]$_S$ sandwich composites and properly captures shapes and through-thickness location of interlaminar failures occurring within the impacted composite skin.

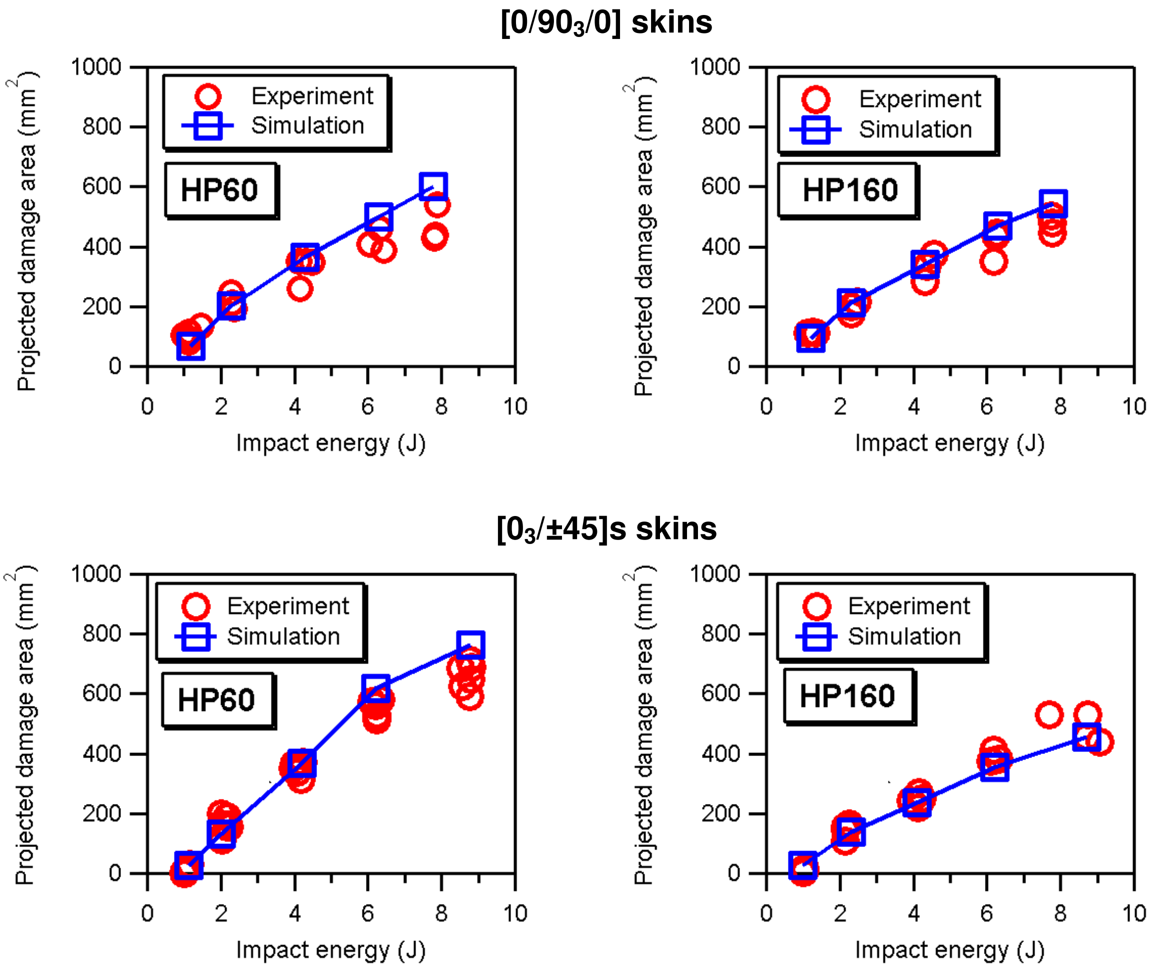

Fig. 8: Comparison between predicted and experimental projected damage areas for sandwich plates with [0/90$_3$/0] (top) and [0$_3$/±45]s (bottom) skins and HP60 and HP160 cores.

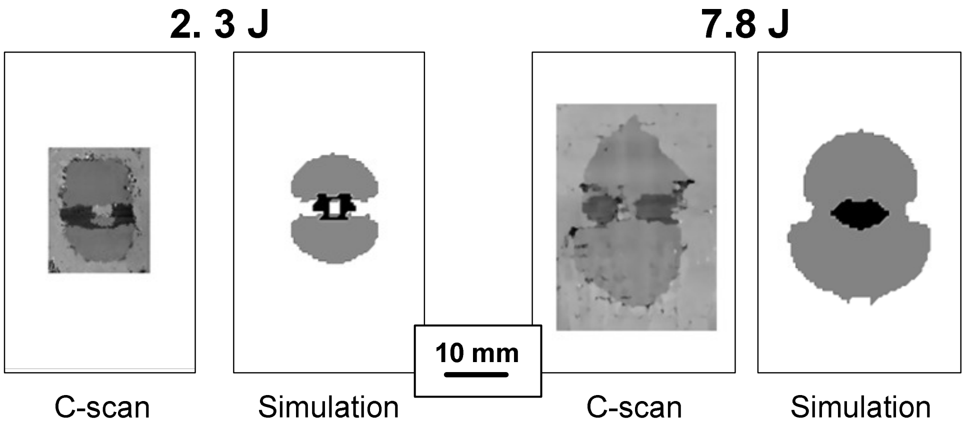

Fig. 9: Comparison between ultrasonic C-scans and predicted delaminated areas for [0/90$_3$/0] sandwich panels with HP60 core impacted at 2.3 J (left) and 7.8 J (right). Different gray levels correspond to different delamination depths.

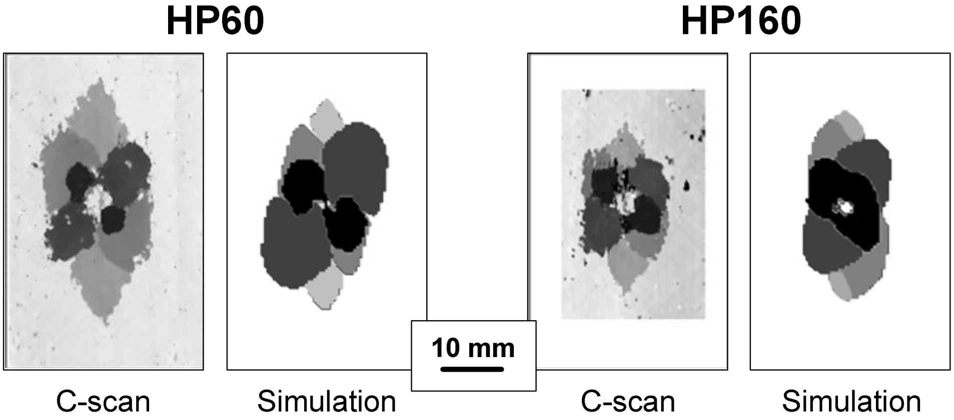

Fig. 10: Comparison between ultrasonic C-scans and predicted delaminated areas for $[0_3/\pm45]_s$ sandwich panels with HP60 (left) and HP160 core (right) impacted at 6.3 J. Different gray levels correspond to different delamination depths.

5. Conclusions

Impact tests were carried out to characterize the nature and extent of damage occurring in sandwich panels with graphite/epoxy skins with two layups ($[0/90_3/0]$ and $[0_3/\pm45]_s$) and PVC foam cores with three densities (65, 100 and 160 kg/m^3).

The density of the core significantly affects the structural response to impact of both $[0/90_3/0]$ and $[0_3/\pm45]_s$ sandwich panels, with higher core densities corresponding to stiffer force-displacement curves and higher peak loads. In contrast, core density does not appear to have a significant effect on the type and temporal sequence of the main damage modes induced by impact, even though the projected damage areas of $[0_3/\pm45]_s$ sandwich panels decreases with increasing core density. The predictions of an FE model recently developed by the authors to simulate the impact response of composite sandwich panels are finally compared with data and observations collected during the experimental analyses.

Acknowledgements

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