EXPERIMENTAL STUDY OF IMPACT DAMAGE RESISTANCE AND TOLERANCE OF E-GLASS/EPOXY SKINNED SANDWICH PANELS

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Abstract

An experimental study of in-plane compressive behaviour of E-glass/epoxy-skinned sandwich panels was conducted. Two cross ply E-glass/epoxy skin thickness combinations of 8/8 and 16/16 plies were impact damaged with their dominant damage mechanisms being characterised. All impact-damaged and baseline panels were in-plane compression tested. The effects of impact damage, skin thickness, on CAI strength were examined.

1. Introduction

Composite sandwich structures have been widely used in the aerospace, marine, automotive, railway and wind energy industries because of their high specific bending stiffness and strength against distributed loads. They have increasingly been expected to be damage-tolerant and energy-absorbing under concentrated impact loads. A multitude of damage mechanisms could occur over a range of impact energies so that their subsequent residual in-plane compression (popularly known as compression-after-impact (CAI)) performance is affected most. When the variation of skin thickness and lay-up, panel symmetry and core density was added, the combined effects on the CAI behavior of the sandwich panels become extremely complex. This has highlighted the need for a thorough understanding of the in-plane compressive behaviour of sandwich structures, in order for these sandwich panels to be effective against localized impacts.

The research programmes at Loughborough University have been carried out to systematically investigate the in-plane compressive behaviour of intact and impact-damaged composite sandwich panels. In two early reports [1-2], damage mechanisms in both aluminium and nomex honeycomb sandwich panels induced via both impact and quasi-static loads were ascertained; the effects of skin thickness, core density and material, indenter nose shape, panel diameter and support condition on the damage characteristics were studied. The energy-absorbing characteristics of the identified damage mechanisms were examined. In a subsequent report [3], the in-plane compressive behaviour of intact and impact-damaged symmetric sandwich panels with aluminium honeycomb core was discussed. This paper presents results of a further investigation of how the variation of skin thickness in a different skin material affects the in-plane compressive behaviour of composite sandwich panels. The use of the E-glass/epoxy skins was intended to gain the insight of damage propagation in in-plane compression, as well as further understanding the mechanisms of impact damage, without the aid of either destructive or non-destructive evaluation.

2. Sandwich panel manufacture and preparations

The cross-ply E-glass/epoxy skins of 300×300 mm with two different thicknesses were made with a UD prepreg of PPG1062/LTM26 in a lay-up of $(0/90)_{2s}$ and $(0/90)_{4s}$, respectively. They were cured in an autoclave at 60°C under a pressure of 0.62 MPa (90 psi) for 6 hours. A 12.7 mm thick 5052 aluminium honeycomb core with a density of 70 kg/m^3 was used. The 0° direction of glass fibres within the skins was aligned with the ribbon direction of core. Each skin was separately bonded to the core in an oven at 60°C for 6 hours under a pressure of 0.1 MPa (15 psi) with VTA260 adhesive. The sandwich panel was then cut into two nominal 200 mm×150 mm specimens with the longer side aligned with the direction of compressive loading. All sandwich panels had their ends potted in epoxy and machined to enhance initial contact with patens of testing machine. Back-to-back strain gauges were then bonded on the panel surfaces at selected locations in both the longitudinal and transverse directions (see Fig. 1) to monitor global and local strains.

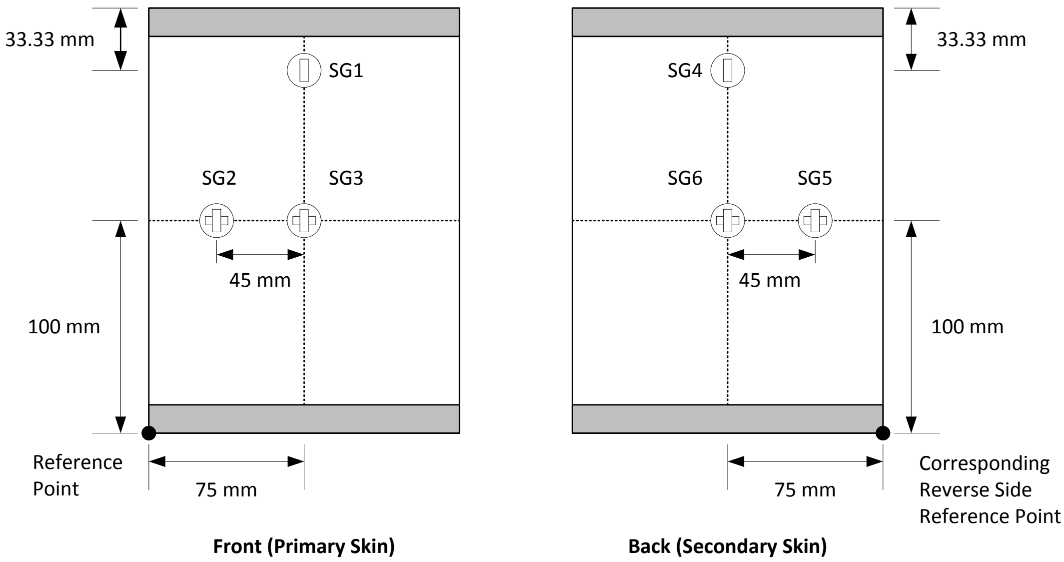

Figure 1. In-plane compressive panel showing specimen dimensions and strain gauge locations

3. Experimental Procedures

3.1. Drop Weight Impact Test

Impact tests were carried out on an instrumented drop-weight impact rig shown in Fig. 2 by using a hemispherical impactor of 20 mm diameter with a 1.49 kg mass. Impact energies (incident kinetic energies - IKEs) were regulated by selecting desired drop heights and ranged from 5 J to 40 J in this investigation. Each rectangular sandwich panel with a circular testing area of 100 mm in diameter was clamped by using a clamping device, the same for both thin and thick skin panels. Both impact and rebound velocities were measured respectively and this allows absorbed energies to be calculated directly, along with impact forces. Dent depths of all the impacted panels were measured. At some impact energy levels, selected impacted panels were diametrically cut up to double check damage mechanisms.

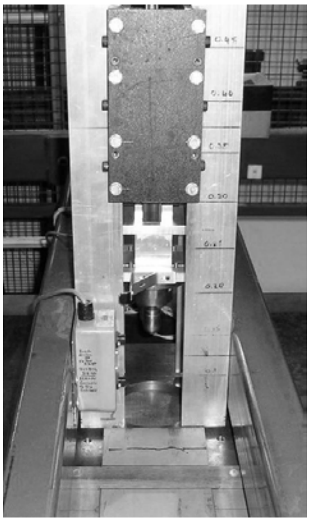

Figure 2. Instrumented drop weight impact test rig

3.*2. In-plane Compression Test*

In each in-plane compression test, a panel was placed in a purpose-built support jig, as illustrated in Fig. 3. The jig provides simple support along the unloaded edges, which were free to move in the width direction during loading. Quasi-static load was applied to the panel at the machined ends via a Denison testing machine at less than 0.5 mm/ min. Load, strain and cross-head displacement in all tests were recorded. All tested panels were cut up for study of damage mechanisms. The loading direction coincided with the 0^0 fibres in the skins.

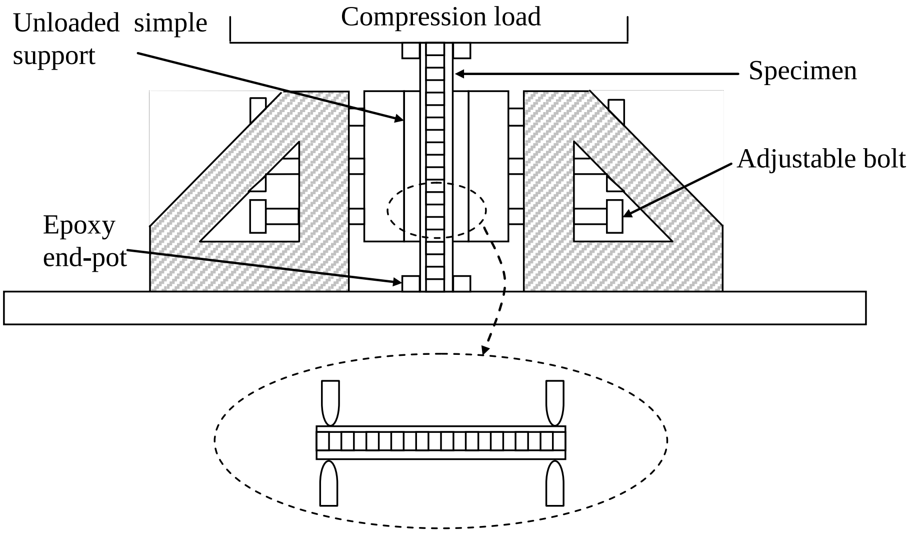

Figure 3. In-plane compression test set-up

4. Damage Characteristics of Impacted Panels

Impact damage inflicted in the E-glass/epoxy panels was very evident due to the translucency of the skins without the need for destructive inspection. Fig. 4 shows an example of a surface image of a panel impacted at 15 J, in which two annular ringed areas surround the central circular area as indicated by the 3 dashed circles. The centrally circled area shows a uniform creamy colour without a visibility of honeycomb cells underneath. It indicates a mix of delamination in the impacted skin, debond and core crush. In the immediate annular ring, although the skin and honeycomb cells are still visually separable, the walls of individual honeycomb cells underneath became much thickened, suggesting a limited crushing of those cells in the immediate bonding region with the skin. This forms a clear contrast with the outer annular ring, in which open cell spaces are clearly separated from the slightly blunted cell walls. Towards the dashed circular line, the cell walls became much less visible, as from there outwards they remain pretty much intact. This affected area is in a shape of a depressed dent in the impacted skin as shown in Fig. 5. Several panels impacted at various levels of IKEs were cut up with the respective extents of crushed core and skin delamination measured. A cross section of one cut up panel, impacted at 18 J, as shown in Fig. 6 confirms a mix of a single delamination, debonds and crushed core. Core crush extent can be seen to be extending much beyond the delamination extent. In all impacted panels, their respective bottom skins remain undamaged, though those impacted at the higher end of impact energies show a shallow dome in addition to fibre fracture at impact location.

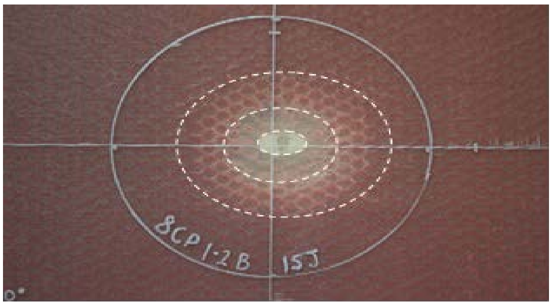

Figure 4. Damage mechanisms in an 8/8 CP E/glass skinned sandwich panel impacted at 15J

Figure 5. Dent depth in an 8/8 CP E-glass/epoxy skinned sandwich panel impacted at 25J

Figure 6. A cross section of a16/16 CP E-glass/epoxy skinned sandwich panel impacted at 18J

The four identified damage mechanisms of core crushing, skin delamination, skin fibre fracture and skin-core debond could occur both sequentially and in parallel, though in general the latter two occur after the first two at relatively high IKEs. Their respective initiation and propagation characterise the impact damage performance of these sandwich panels as shown in Figs 7-9 in terms of crushed core extent, delamination extent and dent depth against IKE. The 70 kg/m^3 core has the lowest resistance threshold and was easily crushed first. Their extrapolated crush thresholds shown in Fig. 7 were dependent on skin thickness. The thicker the skin was, the greater shielding it provided to the core. An initial sharp increase of the lateral extent of crushed core (as well as in the impact direction) leads to the promotion for the occurrence of delamination in the impacted skin shown in Fig. 8. Once the delamination started propagating, the rate of the lateral extent of crushed core decreased substantially. Moreover, the lateral extents of crushed core from both thin and thick skins became inseparable, suggesting an increased localisation after the occurrence of delamination. This localisation intensified when the extent of delamination quickly levelled off, indicating the significant increase of core crushing in the impact direction. This eventually led to fibre fracture beyond 35 J for the thin sandwich panels, by which 95% of the IKE was absorbed. In addition, that the delamination extent in the 0° direction is marginally higher than in the 90° direction is expected, as the flexural rigidities in the former were fractionally greater than those of the latter. This resulted in an oblong shape of the delaminated area.

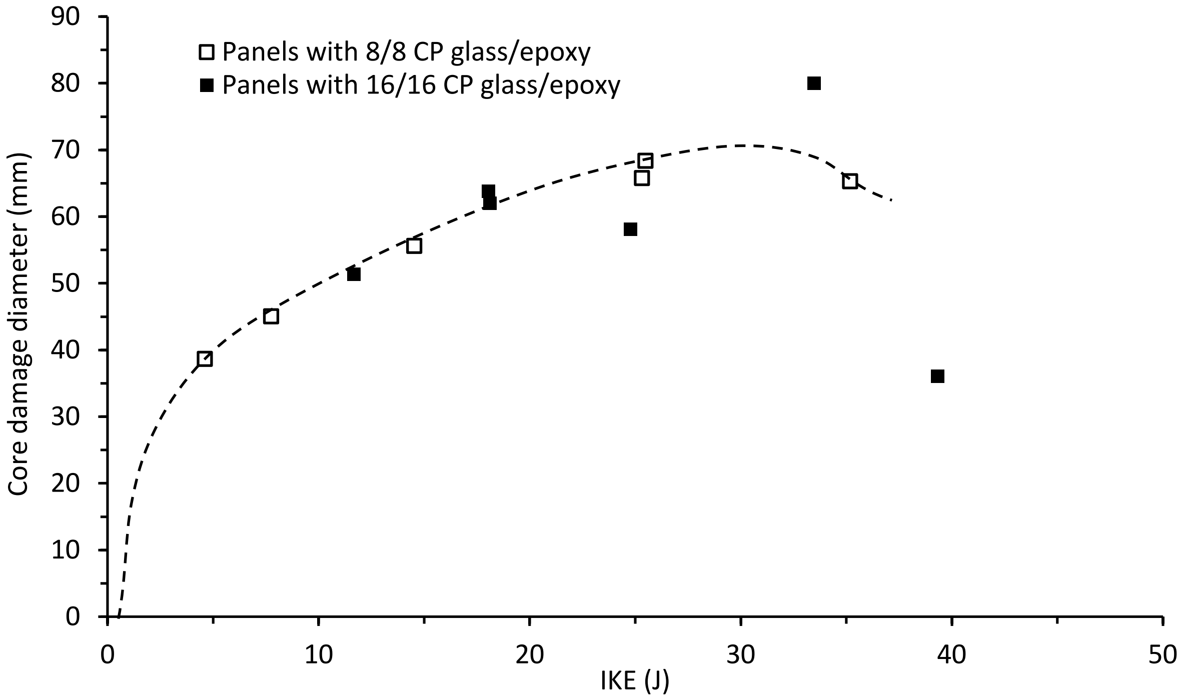

Figure 7. Core crush diameter vs IKE for E-glass/epoxy skinned sandwich panels

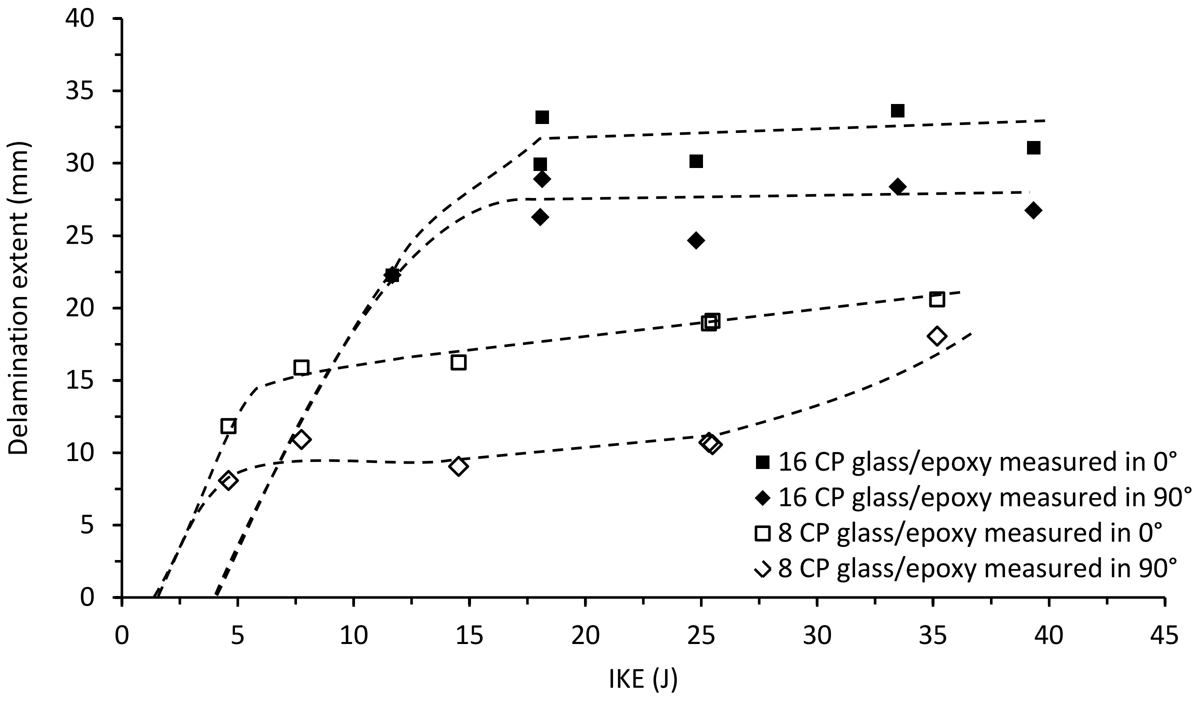

Figure 8. Delaminations vs IKE in 0° and 90° directions of E-glass/epoxy skinned sandwich panels

In sandwich panels, a residual dent depth generally indicates largely a degree of core crushing in the impact (or thickness) direction. Thus, the thicker the skin was for a given IKE, the less dent depth was obtained, as shown in Fig. 9. Contrary to the development of crushed core and delamination extents, the dent depths were smaller initially, less sensitive to skin thickness and started increasing with the increase of damage localisation. Naturally, the thin skin provided the less protection to the core underneath than the thick one and thus had much greater dent depth.

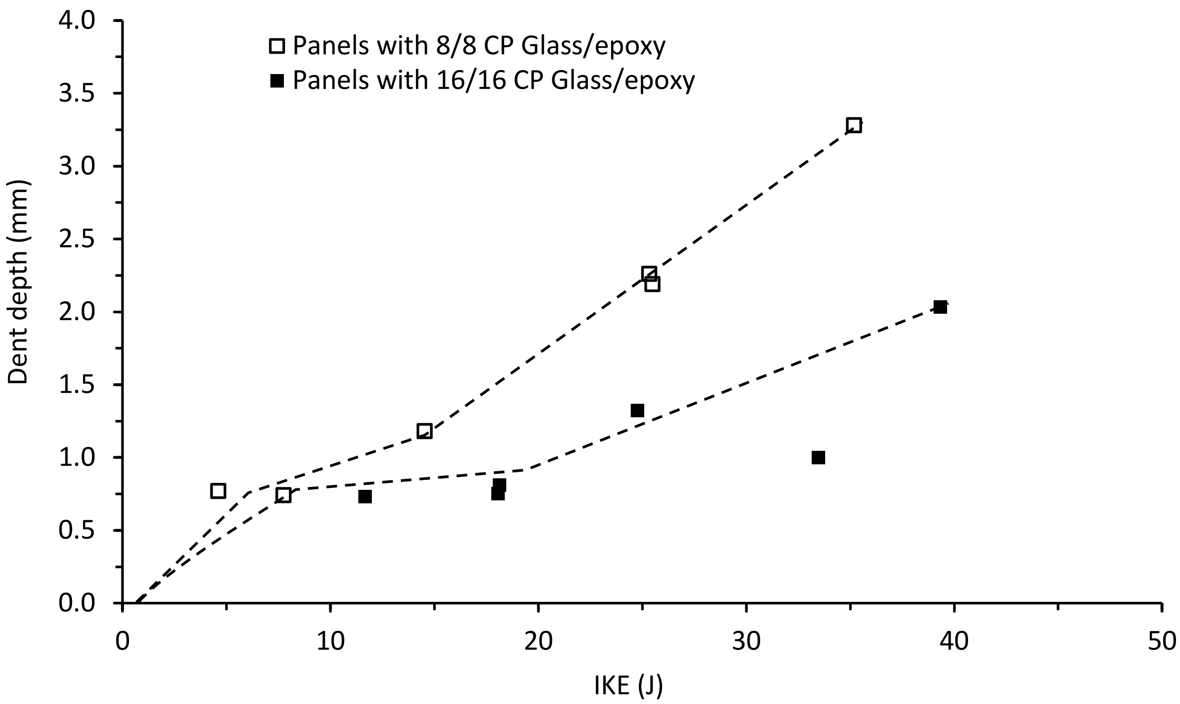

Figure 9. Dent depth vs IKE for E-glass/epoxy skinned sandwich panels

5. Results of In-plane Compression

For the selected width-to-thickness and aspect ratios, intact or baseline E-glass/epoxy sandwich panels always failed prematurely close to one of ends, irrespective of panel thickness. This problem extended into the majority of the thick impact damaged panels, approving to be very 'damage tolerant'. Their in-plane compressive strengths were clearly underestimated. Nevertheless, one of the thick panels that failed in the mid-section region is shown in Fig. 10. Due to the translucency, the original impact damage (enclosed by the dashed line) and its subsequent propagation during in-plane compression can be seen clearly. It appears that the impact induced delamination(s) in the central region could have instigated drastic local instabilities in the mid-section region, leading to the failure. The core crush pattern revealed at the unloaded edges shows the longitudinal sinusoidal mode of in-plane compressive failure, as similarly reported in [3]. Through the thickness fracture is also evident on the impacted skin along the transverse direction.

The thin impacted E-glass/epoxy panels responded as expected with all impact damaged panels experiencing failure in the impact damaged mid-section region. The equal contribution from the two identical skins to the compression resistance was lost, a longitudinal shearing of the core was present in all specimens, propagation of debonds and delaminations from the impact caused local instability in the mid-section region. These thin E-glass panels exhibit a very good tolerance to impact damage as shown in Fig. 11 with only a slight drop (around 25%) in residual compressive strength between 5 and 35 J.

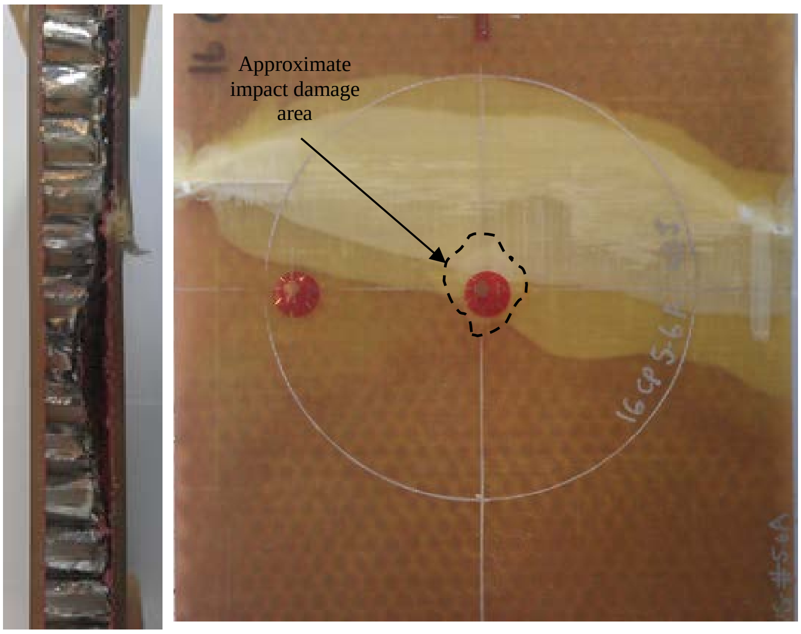

Figure 10. A side and front view of an impacted E-glass/epoxy skinned sandwich panel after CAI test

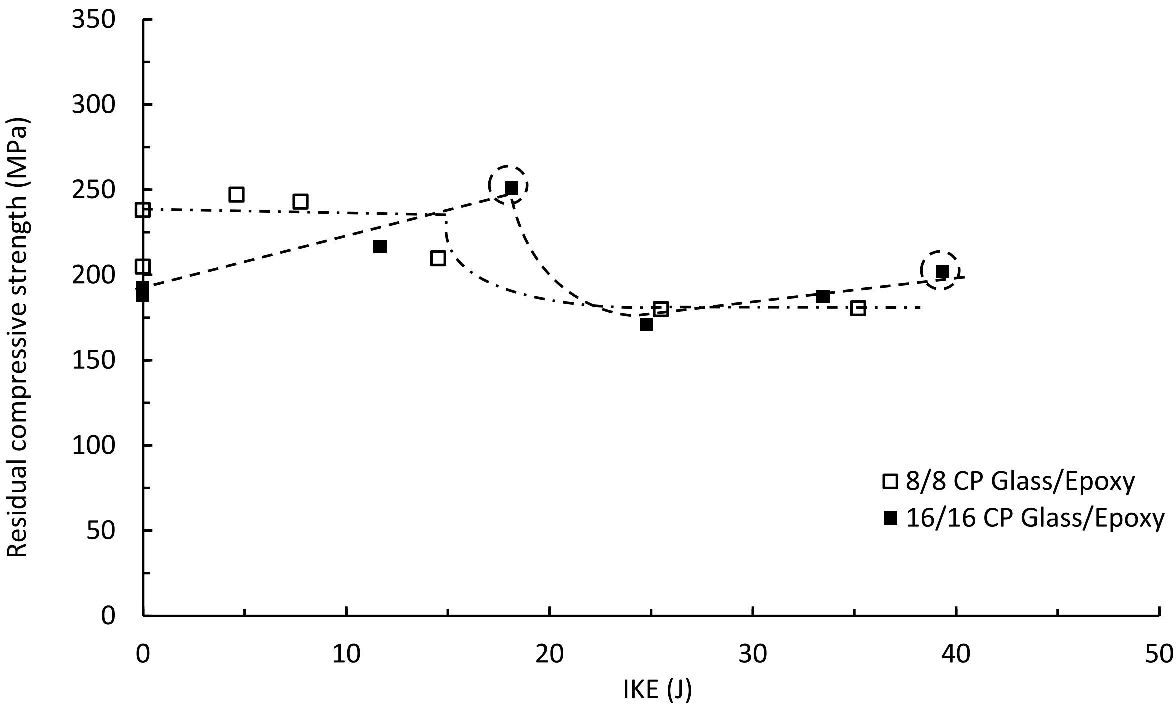

Figure 11. Residual compressive strength vs impact energy for E-glass/epoxy skinned sandwich panels

The conventional procedure of assessing impact damage tolerance requires the residual compressive strengths to be normalised with respect to an average baseline value, giving residual compressive strength factor. This is shown in Fig. 12 in terms of dent depth. It can be seen that these trends look similar to those shown in Fig. 11, suggesting that dent depth could be a useful damage measure, as it combines both damage indication and reflection of local curvature. Nevertheless, the tolerance of impact damage could not be properly assessed, as both baseline and impact damaged panels did not fail in the similar way except for those two circled (in Fig. 11).

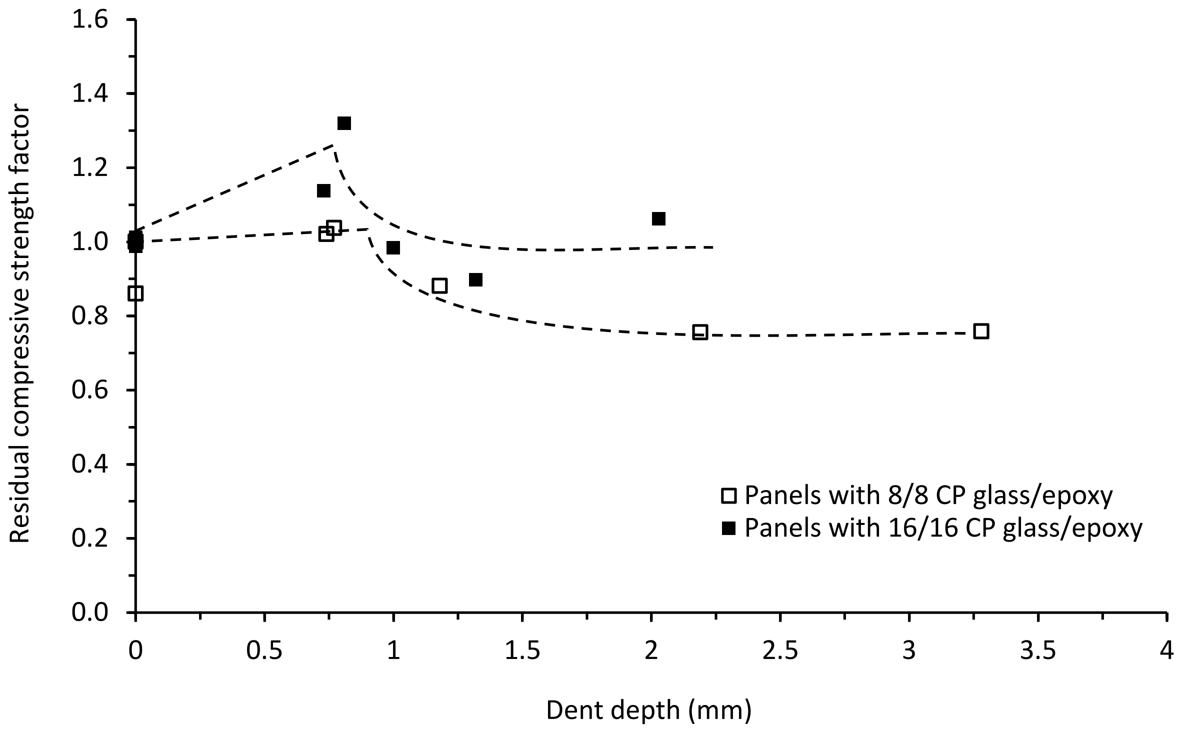

Figure 12. Residual compressive strength retention factor vs dent depth for E-glass/epoxy skinned sandwich panels

6. Conclusions

Symmetrical thin and thick E-glass/epoxy skinned sandwich panels were impact-damaged with their performance characterised comprehensively. Both intact and impact-damaged panels were then subjected to in-plane compression. These panels with translucent skins improved not only the quality of the impact damage characterisation but also the subsequent monitoring of potential growth of the impact damage characteristics during in-plane compression. Whilst the impact-damaged thin panels performed well with all of them failing around the mid-section region, the thick panels did not. Both demonstrated very good impact damage tolerance, though further work will be needed.

References

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