INVESTIGATION OF IN-PLANE COMPRESSIVE BEHAVIOR IN UNSYMMETRICAL COMPOSITE HONEYCOMB SANDWICH PANELS

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Abstract

Four types of unsymmetrical composite sandwich panels were fabricated with two different skin thicknesses, each in two different lay-ups. While some were intact and/or had a central portion of core removed, the rest of them were impact damaged with energies ranging up to 60 J. Their damage characteristics were established, including the role sharing characteristic of energy absorption between the skins and core. All panels were tested in in-plane compression for their compressive strengths with their unloaded edges simply supported. Impact damage in the thicker skins of panels was shown to even up the in-plane compression resistance of the two skins such that its effect on their CAI strengths was reduced. While the variation of a skin lay-up did not have any effect on their CAI strengths, the variation of skin thickness was found to have the most significant effect on CAI strengths. It was shown that the thin unsymmetrical panels did not suffer much reduction in their CAI strengths up to 18J.

1 Introduction

In two companion papers [1-2], the impact damage characteristics of both symmetrical and unsymmetrical carbon/epoxy skinned honeycomb sandwich panels were provided [1] and the compression-after-impact (CAI) strengths of symmetrical sandwich panels were presented [2], following the panel compression approach. The panel compression approach describes an in-plane compression testing set-up, in which the unloaded edges of rectangular panels are simply supported (i.e. knife edges), similar to the CAI set-up for monolithic laminate panels [3]. Distinguishing this support condition for unloaded edges from others was very important, as it could affect the in-plane compressive and thus CAI strengths of sandwich panels significantly. This paper focuses on the CAI strengths of intact and preconditioned unsymmetrical sandwich panels. Four different panel configurations were used, including two combinations of unequal laminate skin thicknesses. The paper examined how the lack of symmetry in sandwich panels affected their in-plane compression failure and how such failure was affected by skin thickness and skin lay-up in addition to damage characteristics.

2 Sandwich panel design

Carbon/epoxy laminate skins were made in a lay-up of cross ply (CP), quasi-isotropic (QI) and multi-directional (MD) and were composed of 6, 8, 12 and 16 plies. Two different combinations of unequal skin thicknesses were used with the same ratio of thin to thick skins of 0.75 in the construction of ‘thin’ and ‘thick’ unsymmetrical panels. For unsymmetrical panels with skins in a CP lay-up, the skin thickness combinations were 8 plies in $(0^0/90^0)_{2s}$ versus 6 plies in $(0^0/90^0/0^0)_s$ and 16 plies in $(0^0/90^0)_{4s}$ versus 12 plies in $(0^0/90^0)_{3s}$, respectively. In the thin panels, the number of 0^0 plies in each skin remained the same, whereas in the thick panels, the thicker skin had two more 0^0 plies than the thinner side. In addition, the plies at the symmetrical plane in the thicker side of thin unsymmetrical panels were 90^0, whereas the plies at the symmetrical plane in the thinner side were 0^0. For thin and thick unsymmetrical panels with skins in QI and MD lay-ups, the skin thickness combinations were 8 plies in $(45^0/0^0/–45^0/90^0)_s$ versus 6 plies in $(45^0/0^0/–45^0)_s$ and 16 plies in $(45^0/0^0/–45^0/90^0)_{2s}$ versus 12 plies in $(45^0/0^0/–45^0)_{2s}$, respectively. Thus the fundamental differences of the two skins here were that the MD lay-up had no 90^0 plies in both thin and thick panels. As a result, the plies at the symmetrical plane in the QI lay-up were 90^0, whereas the plies at the symmetrical plane in the MD lay-up were $–45^0$.

3 Sandwich panel manufacturing and preparation

All laminate skins were cured in an autoclave. A honeycomb core of 5052 aluminium had a core thickness of 12.7 mm and a density of 70 kg/m^3. Skin-core bonding of took place in an oven. A bonding of unsymmetrical sandwich panels with the removed core followed the same procedure as in [2]. Unsymmetrical sandwich panels had nominal thicknesses of 14.45 mm and 16.2 mm, respectively. All other material and manufacturing details are available in [1-2]. The preparations of current unsymmetrical panels for in-plane compression testing were the same as those for symmetrical panels, as given in [2] and are shown diagrammatically in Figure 1.

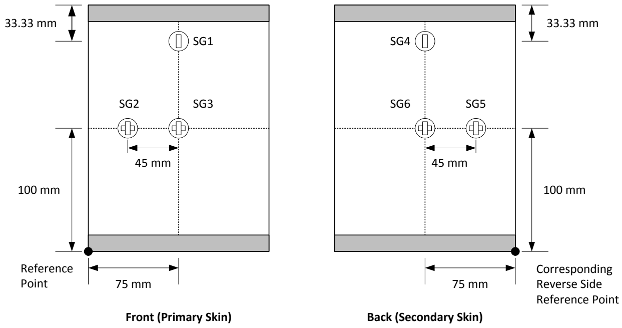

Figure 1. Illustration of strain gauge location and panel set up for in-plane compression testing.

4 Impact damage characteristics and energy absorption

Damage mechanisms in impacted sandwich panels were examined extensively using visual inspection, cross sectioning and impact response curves. Their damage characteristics over IKE ranges were established in terms of interior damage extents on the cross section in the transverse direction, absorbed energy, dent depth and maximum impact force, which are discussed fully in [1]. A diagrammatic representation of the damage mechanisms are shown in Figure 2. Separation between the core and the skins was never observed before ply fracture from all cross sections and bottom skins remained intact on all occasions.

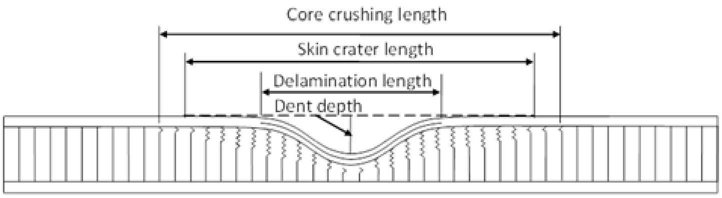

Figure 2. Illustration of observed and measured damage characteristics seen in impacted sandwich panels.

In both thin and thick unsymmetrical sandwich panels, impact damage was created on their thicker sides, i.e. 8 ply and 16 ply skins, respectively. The impact damage characteristics of the unsymmetrical panels were described in details in [1] along with details of the impact testing set-up. Core crushing and delamination in the impacted skin were found still to be the major damage mechanisms in the impacted unsymmetrical sandwich panels. In particular, the role sharing characteristic of energy absorption also existed between the skins and core. While all other characteristics of unsymmetrical panels were the same as those of symmetrical panels, there was one noticeable difference, relating to thin panels with skins in a QI lay-up. That was, those thin unsymmetrical panels had the significant less delamination extent than either thin panels with skins in a CP lay-up or thicker panels with skins in any lay-up, see Figure 3.

Figure 3, showing delamination extent vs. IKE for both thin and thick panels, indicates that the spread of delamination was initially swift but absorbed little energy and it decayed significantly from the delamination extent of about 30 mm onwards. As the front of the larger delaminations was far away from the immediate vicinity of the impact location, its local interlaminar shear (ILS) stresses could be low and thus it was very difficult for the supplied IKE to drive the level of the ILS stresses up further. These parabolic decaying trends suggest that the additional increase of absorbed energy could be due to the generation of multiple delaminations. Interestingly, thick panels with skins in a QI lay-up seemed to show the greater level of delaminations than those with a CP lay-up, though there were only two data points available.

Figure 4 exhibits the extents of core crushing in terms of IKE for both thin and thick symmetrical panels. While all the aforementioned characteristics of the delamination extents are again present, the only other noticeable feature is that the extents of core crushing from both thin and thick panels with skins in a CP lay-up have almost collapsed onto each other, before ply fracture set in. Also confirmed is that thick panels with the QI skins show greater extent than those with the CP skins in accordance with the early observation on their delamination extents. Also, it is likely that the leveling off seen in the trends could be related to the core crushing extent reaching the clamped regions of the panel.

5 In-plane compression testing

The panel preparations for in-plane compression testing included ends potting and machining in addition to strain gauge mounting. Potting the ends of each panel with epoxy required the core to be slightly crushed to a depth of no more than 5 mm (i.e. less than one cell size) at the mid-plane. Then the end of the panel was immersed in the middle of liquid epoxy in a mould. After epoxy cured, the opposite end was potted. The ends of cured epoxy pots were machined to be not only perpendicular to the laminate skins but also parallel to each other. This was a preferred gripping technique in order to minimise stress concentrations and prevent end-brooming failure.

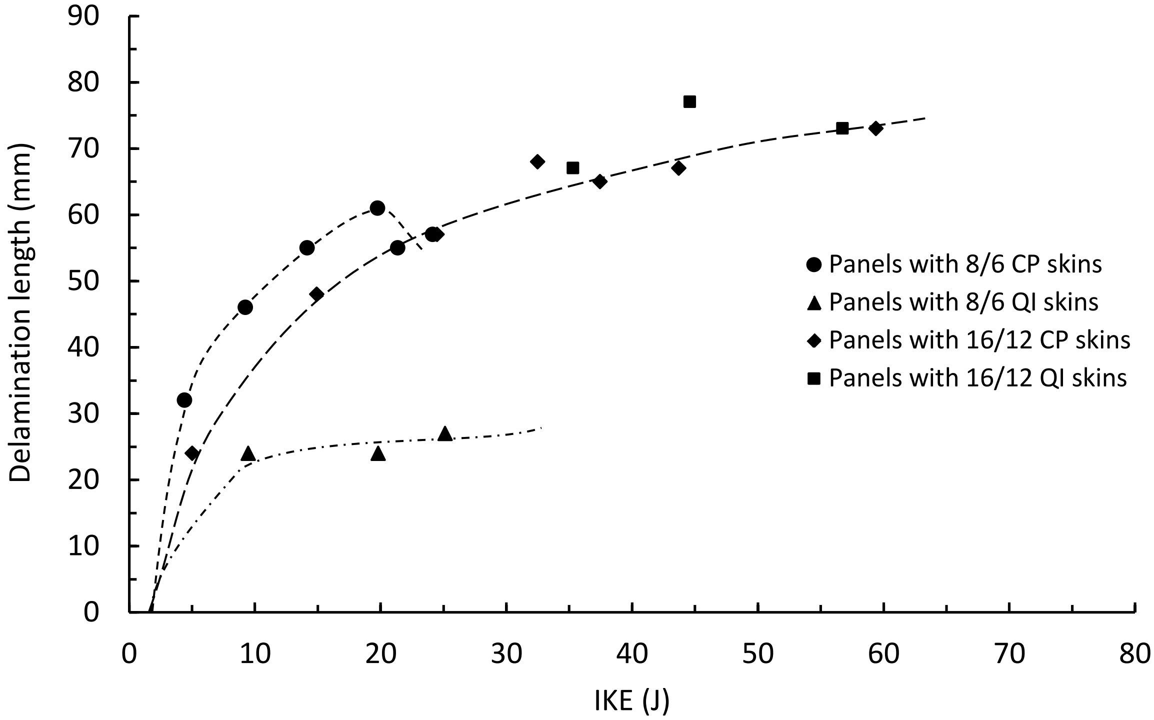

Figure 3. Delamination extent vs. incident kinetic energy for thick and thiun unsymmetrical sandwich panels.

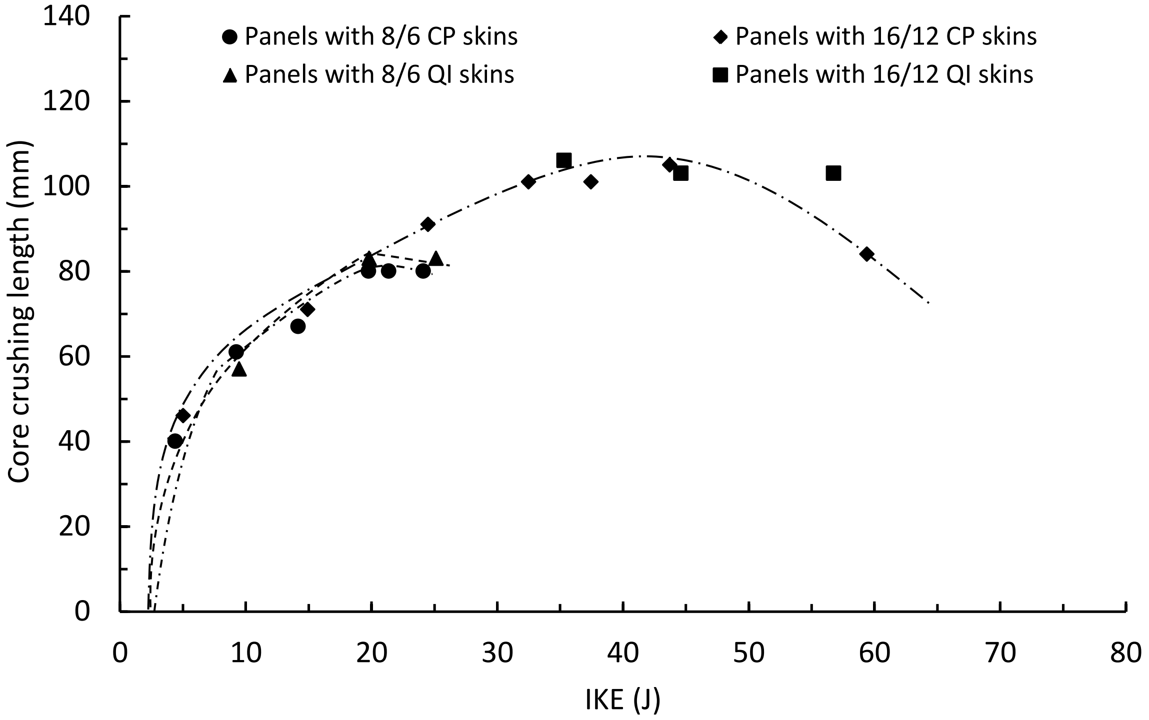

Figure 4. Core crushing extent vs. incident kinetic energy for thick and thin unsymmetrical sandwich panels.

In each in-plane compression test, a panel was placed in a support jig, as illustrated in Figure 5. The jig provided simple support along the unloaded edges, which were free to move in the width direction during loading and rotate out of panel plane. Quasi-static load was introduced to the machined ends of the panel on a Denison testing machine at a speed of less than 1 mm/min. Although the loaded ends were not clamped, they were effectively close to the clamped condition but without surface clamping pressures. Load, strain and cross-head displacement in all tests were recorded through a data acquisition system.

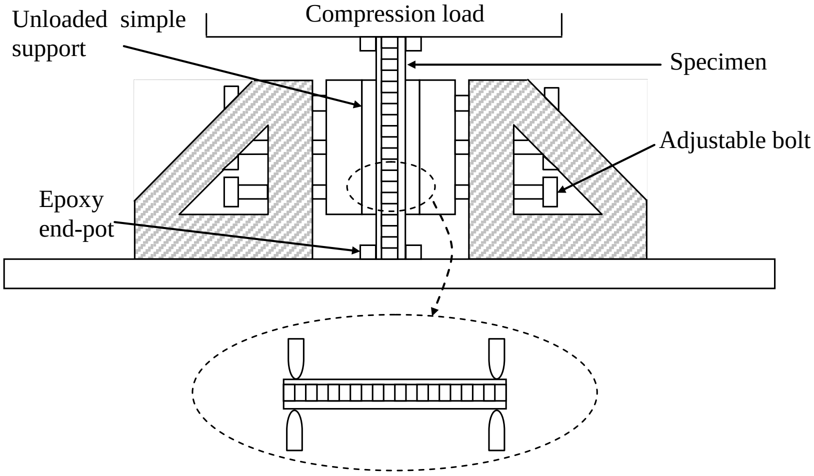

Figure 5. In-plane compression test rig setup

6 Behaviour of control panels

As emphasised in [2], using the panel compression approach, the width-to-thickness ratios of current sandwich panels were relatively small and, unless impact-damaged, the intact panels did not fail in in-plane compression in the mid-section region before failure occurred at a region close to one of their ends. This kind of premature failure could potentially underestimate their baseline compressive strength values. With the given aspect ratio of the panels, such underestimation could become severer for panels with thicker skins (see below in this paragraph). Thus the establishment of an understanding of their in-plane compressive behaviour in terms of stress-strain responses was extremely important [2,5-6] to not only ascertaining how the preconditions such as impact damage reduced the in-plane compressive strengths, but also providing the baseline in-plane compressive strength value with some degree of physical insight, benefiting the impact damage tolerance assessment. However, unlike the intact symmetrical panels with two identical skins, the two skins of intact unsymmetrical sandwich panels were not identical and were unable to provide the equal compression resistance to begin with, adding the significant complexity. Figure 6 shows the in-plane compressive responses from an 8/6 CP control panel as well as an 8/6 CP core removal specimen response. Clearly, no local buckling can be seen in the control panel response, as opposed to the very early onset of mode reversal in the core removal panel leading to a very premature failure, and a large reduction in compressive performance, highlighting the importance of the cores contribution to the in-plane compressive strength, this figure signifies a failry standard response from the control panels. The apparent average baseline compressive strength of 270±69 MPa for unsymmetrical panels with 8/6 skins in a CP lay-up was roughly the same as the apparent average value of 296±36 MPa for symmetrical panels with 8/8 skins in a CP lay-up. Similar to the case of symmetrical panels (with CP skins), doubling the skin thickness in unsymmetrical panels with CP skins led to 28% reduction of apparent average compressive strength value (down to 195 MPa).

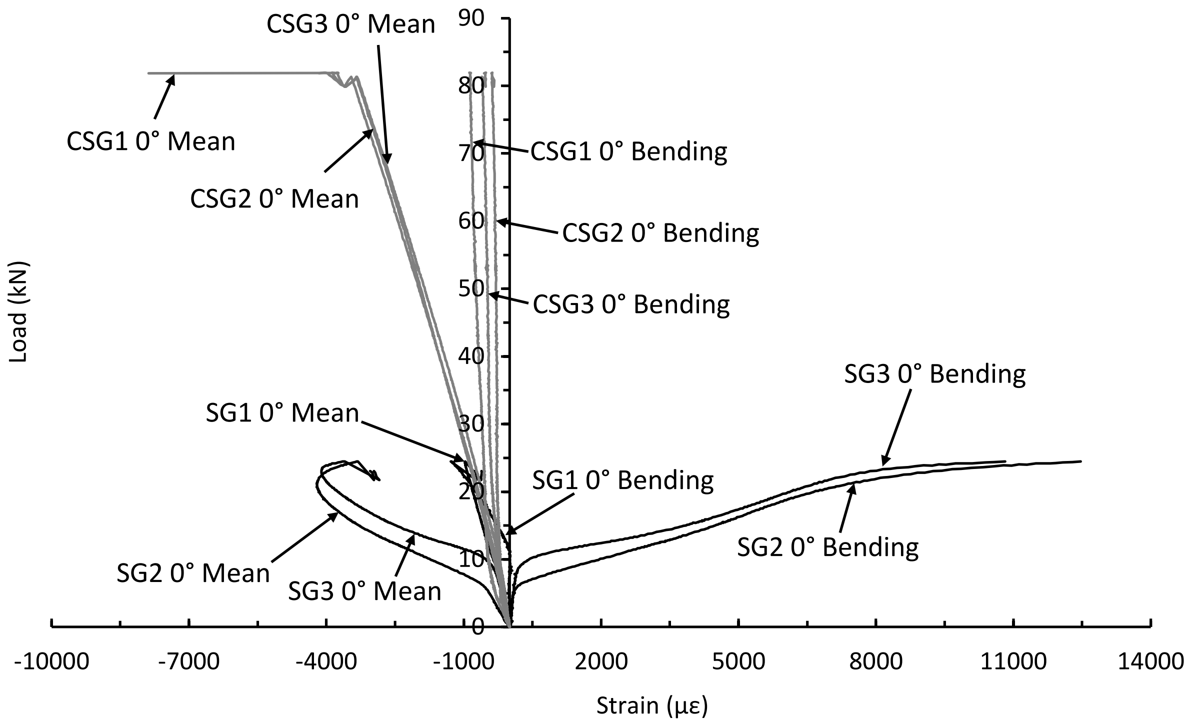

Figure 6. Mean and bending strain in the 0° (loading) direction vs. load response from an 8/6 CP control panel and an 8/6 core removal panel

7 Discussion of CAI results

Evaluating the effect of impact damage in unsymmetrical sandwich panels on their in-plane compressive strengths was very difficult due to their lack of symmetry as well as the role sharing characteristic of energy absorption, which could collectively counteract the effect of impact damage. Therefore, a developing trend of CAI strengths or strains with an increase of IKE may not be monotonically decaying. Figure 7 shows the CAI performance of thin unsymmetrical panels with 8/6 ply skins in a CP lay-up. It is interesting to observe that these panels were as if very damage-tolerant up to about 18J without suffering much reduction in their CAI strengths, though the baseline compressive strength values were scattered. Around 18 J, typical damage extents in the impacted skins could be around 55 mm in diameter (in the panel width direction) (Fig. 9 of [1]), which was more than sufficient to induce a substantial reduction of the CAI strengths. This forms a stark contrast to the CAI strength data trend of symmetrical sandwich panels with 8/8 skins in a CP lay-up (see Fig. 10 of [2]), in which the CAI strength reduction was almost immediate from a couple of joules onwards. This seems to confirm that the impact damage inflicted in the thicker skins of unsymmetrical panels evened up the effective in-plane compression resistance of the two skins such that its deleterious effect on the CAI strengths was ‘cancelled out’. Beyond 18 J where ply fracture occurred, the CAI strength values decreased further. A further examination of thin unsymmetrical panels with 8/6 ply skins in QI and MD lay-ups also shown in Figure 7 reveals that the values of CSRF actually increased slightly up to about 15 J due to this cancelling effect and started to decrease only when ply fracture occurred. This trend was pretty much the same as that of the thin panels with 8/6 skins in a CP lay-up. This also suggests that these thin unsymmetrical panels may not perform as well as symmetrical panels in in-plane compression when they were not damaged but could perform much better if impact damaged while being two plies less (thus substantially lighter).

Another significant potential reason for the above non-singular decaying trends of CAI strengths of thin unsymmetrical sandwich panels could come from a contribution of the aforementioned role sharing characteristic of energy absorption. The fact that the delamination extents in the impacted skins of the thin unsymmetrical panels actually increased by about 71% (from 32 mm to 55 mm) with an increase in IKE from 5 J to 18 J for 8/6 ply skins in a CP lay-up and by 40% (from 20 mm to 28 mm) with an increase in IKE from 5 J to 20 J for 8/6 ply skins in a QI lay-up is that their CSRFs did not decrease accordingly. This was because the most of IKE was absorbed via the core crushing in those cases so that the evened-up skins along the support of core provided the in-plane compressive resistance, almost equivalent to the intact panels. This indicates that it was not just the damage size in the impacted skins that dictated the CAI strengths of the sandwich panels, considering that from 10 J to 25 J, in which the delamination extent in the panels with 8/6 skins in a CP lay-up was significantly greater than that of the panels with 8/6 skins in QI and MD lay-ups.

The CAI results from thick unsymmetrical panels with 16/12 ply skins in a CP lay-up in Figure 8 are slightly scattered. Nevertheless, a steady reduction trend of CSRF values can be seen to be moderate and similar to that of symmetrical panels in [2]. The CAI results from thick unsymmetrical panels with 16/12 ply skins in QI/MD lay-ups are also shown in Figure 8. A substantial CAI strength reduction of these panels was from around 10 J. A further degradation of the CAI strengths (15%) after the occurrence of ply fracture was small, considering that IKE was increased by six times. In addition, the effect of lay-up in these thicker unsymmetrical panels on CAI strengths was small. For these thick unsymmetrical panels, it was difficult to see if the aforementioned role sharing characteristic of energy absorption had any influence over their CAI strengths.

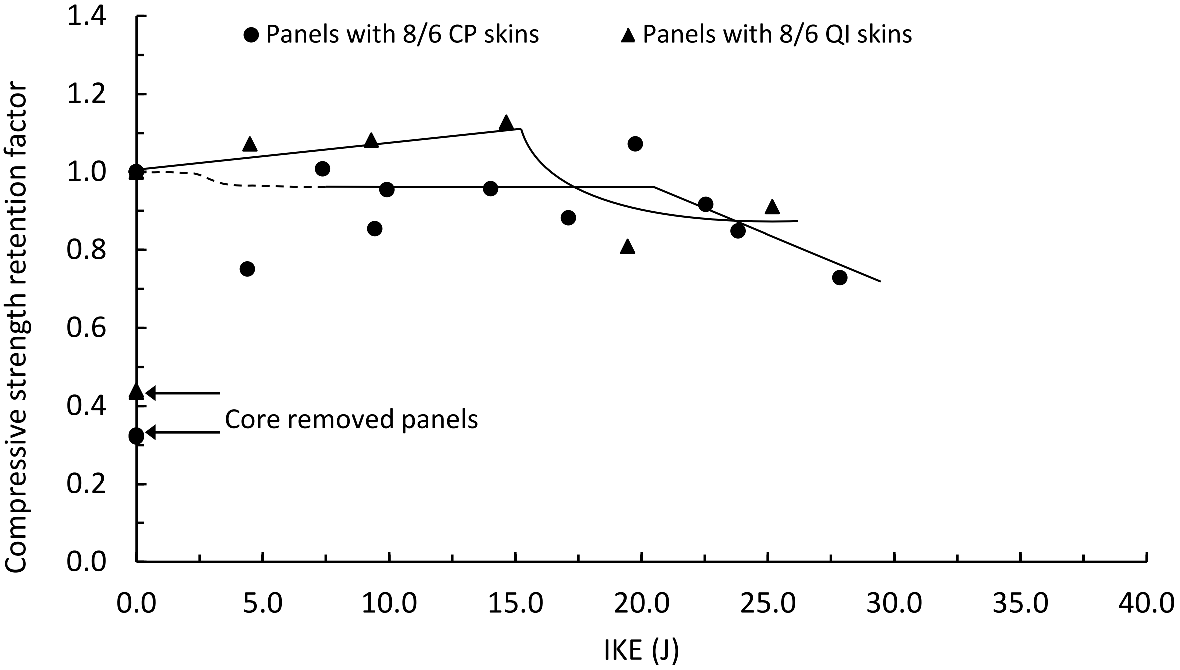

Figure 7. Compressive strength retention factor vs IKE for thin unsymmetrical sandwich panels

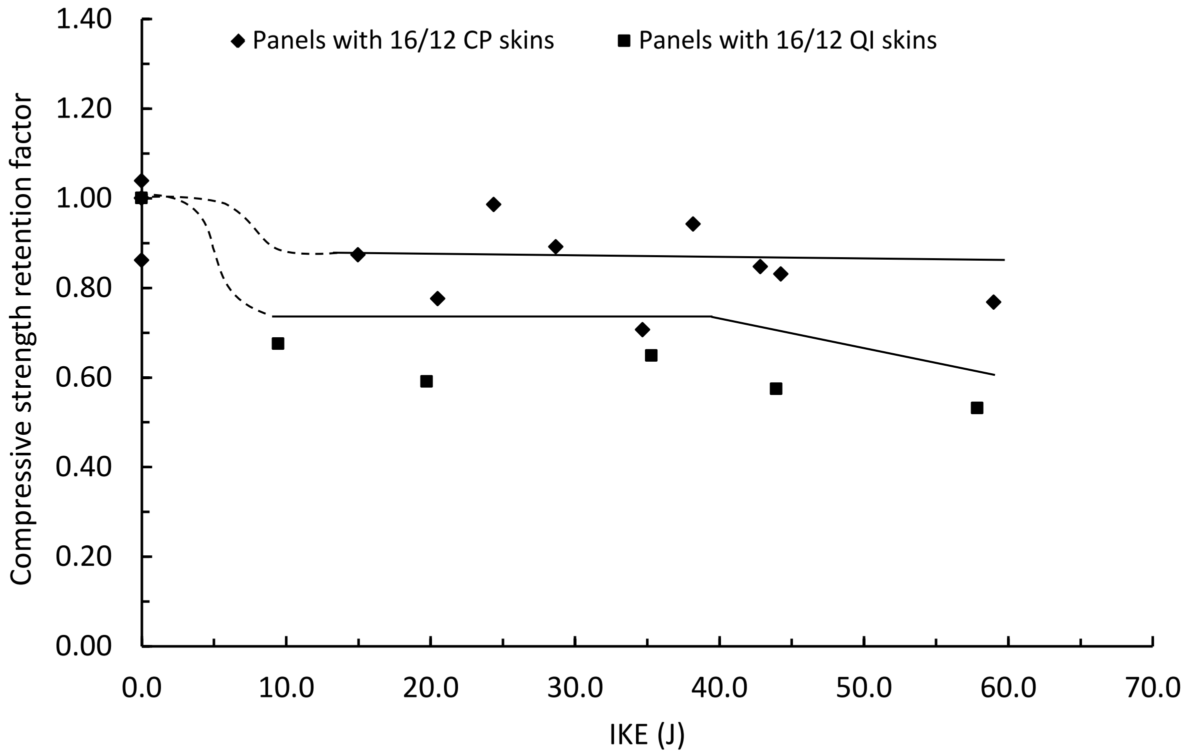

Figure 8. Compressive strength retention factor vs. incident kinetic energy for thick unsymmetrical panels

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