A MINIATURIZED POST-IMPACT COMPRESSION TEST FOR CURVED COMPOSITES

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ABSTRACT

The paper evaluates the use of curved compression after impact specimens as an alternative to the conventional flat laminates. Curved and flat laminates were prepared for glass and carbon fiber composites. The glass fiber composites were produced with different resin types to assess the ability of the curved sample to distinguish between tough and brittle composites. Some laminates were prepared to give a large curved specimen equivalent to full scale Boeing/Airbus flat specimens. Others were use to produce small scale curved samples equivalent to the miniaturized QMW flat specimen. The results indicate that the use of curved samples will indicate different trends concerning the ultimate level of compression strength reduction that is possible in a laminate. The curved specimen will allow differences between tough and brittle laminates to be identified and the small scale curved samples provide similar trends to the full scale curved samples.

1. INTRODUCTION

A major factor impeding the use of composite materials in structural applications in aerospace is the susceptibility of the materials to damage, particularly from impact. The difficulty in detecting sub-surface impact damage, which typically consists of a mixture of delamination, transverse cracking and fibre breakage, means that design allowables are calculated on the presumption that impact damage is present at a level just below that of visible damage (1). Compression after impact tests have become established as the preferred method for assessing the relative damage tolerance of a composite material. There are a number of variations around the theme but the basic approach is to subject a flat plate to an out-of-plane, low-energy impact blow, followed by an in-plane compression test to measure the residual strength. Most testing is currently undertaken on tests that follow the Boeing (2) or similar Airbus (3) standards with a flat plate size of 100 mm x 150 mm and a thickness of 4-5 mm. Smaller tests have been developed including the QMW test which takes a similar ratio of dimensions with a test panel of 89 x 55 mm, typically 2-3 mm thick (4). The specimens are lightly clamped during the impact test and support by anti-buckling guides during the compression test.

The tests are effective in providing a ranking between different material systems although it has been demonstrated that most differences that are observed when plotting the compression strength versus impact energy for different laminates can be traced back to the different extent of impact damage that is introduced at each specific impact energy. When laminates are compared on the basis of the damage width created in the impact test, then the residual compression strength does not differ much (5). There is also a very good correspondence between the rankings between materials determined by the full-scale Boeing/Airbus test and those generated by the smaller scale QMW specimen and fixture (4).

There has however been concern expressed that the compression after impact test is not an ideal test method for generating design data as the test geometry employed gives too much emphasis to the role of delamination in controlling failure. Real component geometries where there is some degree of shape, other than that of a flat plate, provide a greater inherent resistance to buckling and should be more resistant to the damaging effects of delaminations. This was the reasoning behind studies by Davies et al.(6) who studied the compression after impact performance of curved panels using a modified version of the Boeing fixture. The work by Davies et al. showed that the residual compression strengths of carbon fibre prepreg laminates were much higher for a given impact blow if the specimen was curved compared to flat and that the failure seemed to be more dependent on impact induced fibre facture rather than on the growth of delaminations.

The purpose of this paper was to further explore the utility of a curved impact test specimen by assessing its ability to discriminate between different materials systems with different resins and fibres. Furthermore, a miniaturised curved specimen was explored to mimic the earlier development of a miniaturised flat panel. Comparisons are made between the results generated by flat (small), curved (small) and curved (full sized) specimens.

2. IMPACT AND COMPRESSION AFTER IMPACT BEHAVIOUR

When a flat composite plate is subjected to a low energy (non penetrating) impact, the result is usually a combination of different fracture events. Transverse cracks are generated within a ply when the specimen bends under the force of the impactor. These transverse cracks generate stress concentrations in the interlaminar regions that trigger the nucleation of delaminations that grow between layers of different ply orientation. The exact nature of the size and shape of delaminated zones between the different plies is complex and determined by many factors including the stacking sequence, and the stiffness of the plate itself. Stiff plates exhibit damage that cascades through the laminate. High Hertzian contact forces initiate damage in a local zone on the impact face which in turn results in a pine tree pattern of delaminations of increasing size through the thickness o the plate. Thin plates which are more compliant are dominated by flexural failure and a reverse pine-tree pattern of delaminations will be generated. Fibre fracture is also generated, notably around the initial impact contact zone and on the reverse face of the material at positions of maximum tensile stress.

The failure of the damaged flat plate in an in-plane compression test results from a localised buckling at the zone of the delaminations. Gross buckling is usually restricted in a compression after impact (CAI) test by the use of anti-buckling guides at the edges of the specimen. The different modes of local buckling failure possible in damaged flat plates are shown schematically in figure 1. The geometric constraint imposed by using a curved specimen for the impact test are likely to favour buckling mode d and restrict buckling in modes a and b (mode c is rarely observed).
Under these circumstances the influence of fibre breakage on the final failure stress is likely to be more significant than in the case of the simple flat plate.

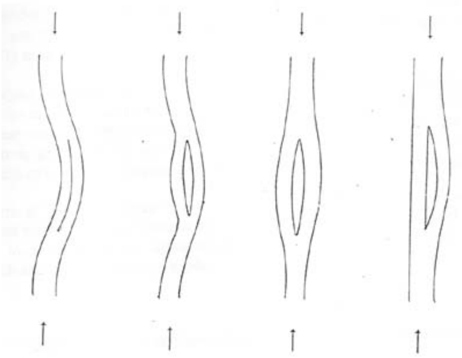

Figure 1. Possible buckling modes in compression for plates with delaminations (after Davies et al)

The behaviour of curved specimens in a CAI test regime was first examined by Davies et al.(6). In their study a CAI rig was used that was based on the Boeing rig used for flat plates with modifications to the rigs to accommodate the curved ends. The shell's dimensions were 150mm x 88mm with a central rise of 18mm. The shell also had a flange to allow clamping to the impact rig. A comparison of results from flat and curved 2mm panels showed that incident energies of 0.7J on the curved plate and 2.5J on the flat plate produced equivalent forces. However the increased forces did not produce delaminations that weakened the curved plate relative to the flat plate as the curved shape increased the inherent resistance to buckling.. The results of CAI testing showed that the 2mm flat plat buckled at a stress of 155Mpa compared to that of 309 MPa for the curved shell. The curved panel buckled inwards in a local blister in the same manner as undamaged plates despite extensive delaminations. Davies concluded that the current emphasis placed on delaminations as the dominant feature controlling the compressive strength after impact might not be valid for structures that are not flat. Similar results were found by Short et al who used different sized specimens, 50 x 200 mm (7).

3. EXPERIMENTAL METHODS

Laminates were prepared for the compression after impact tests using dry fabrics, and a vacuum infusion process. Glass fibre composites were produced using a 0/90 non-crimp fabric, style ELT 566 supplied by Vetrotex. Carbon fibre laminates were produced using a 370 gm^{-2} 6K T300 plain weave carbon fibre fabric, supplied by Cytec Fiberite.

A vinyl ester resin, Norpol 9102-500 from Reichold, was used as the infusion resin for both glass and carbon fibre laminates while further glass fibre laminates were produced with a polyester resin, Crystic 489PA supplied by Scott Bader. To cure the rein, 2% catalyst of Trigonox239 was added to the vinyl-ester and 1% of catalyst M (Scott Bader) for the polyester. The lay-up used for all tests was $[(0/90)_3]_s$. Typical volume fractions achieved were of the order of 47-55%. The glass fibre polyester laminates were 2.7-2.9 mm thick and carbon fibre laminates slightly thinner at approximately 2.5 mm.

Three different types of specimens were prepared. Small flat test plates of the standard QMW test size, 89 x 55 mm; small curved test samples and large curved test samples.

For the large curved laminates, specimens were manufactured using the same dimensions as in the study by Davies et al (6). The curvature has a central span of 88mm and a centre rise of 18mm. The straight edges of the specimens were formed in the mould to have a flat flange of 10mm that was then firmly clamped in the impact rig. They are cut into 150mm long sections for testing, figure 2. The small curved panel was designed in this study to be used in a modified version of the QMW miniaturised test. Each specimen has a central span is 53.5mm and a centre rise of 10.68mm. The straight edges of the specimens were formed in the mould to have a flat flange of 10mm that could be firmly clamped in the impact rig. They are cut into 89mm length for testing, figure 3.

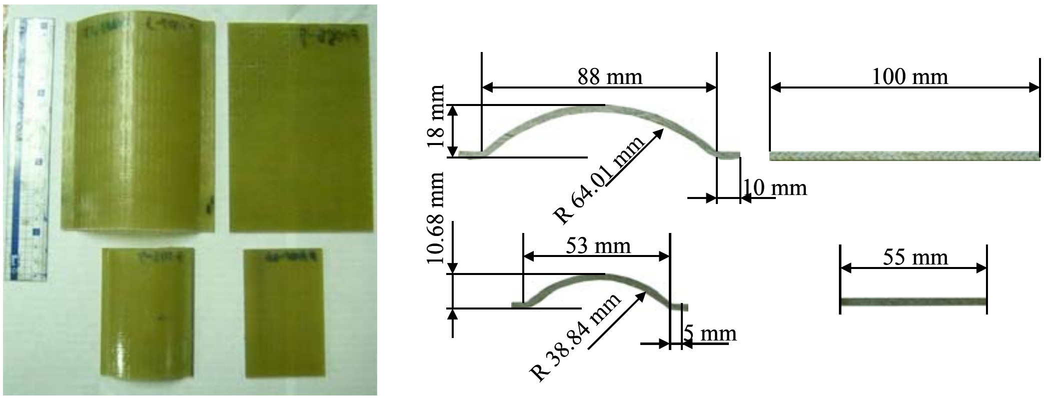

Figure 2: Test specimens and their respective dimensions in the horizontal plane.

The combination of glass, resin and specimens manufactured are listed in table 1.

Table 1. Combination of specimen’s shape and materials

	Vinyl Ester/ELT566	Poly Ester/ELT566	Vinyl Ester/Carbon
QMW-Flat	•	•	•
Small-curved	•	•	•
Large-curved	•	•	•

4. IMPACT TESTS

In the compression after impact test, non-penetrating low velocity impact tests were performed using an instrumented falling-weight impact machine, with data logger and analysis instrumentation supplied by CEAST (DAS4000 and DARTVIS). All tests were performed using a common striker which weighed 0.78kg and was fitted with a 20mm diameter hemispherical tup. An additional 2.9kg mass was added to the striker in order to provide a suitable range of incident kinetic energies. The kinetic energy of the striker, and hence the force generated during the impact blow, was varied by adjusting the drop height of striker. For the flat plate, the geometry consisted of the specimen being simply supported on a steel ring of 40mm diameter, impacted centrally by the falling striker. The specimen was clamped during the test by two compression air clamped bolts. For curved panels it was impossible to clamp the curved specimens using the same clamping rig as the flat specimens. A new clamping rig for curved specimens was developed that restrained the specimens along their long flat edges, Figure 3. This was achieved using two slotted steel plates, held in place by butterfly nuts along these edges and tightened by hand.

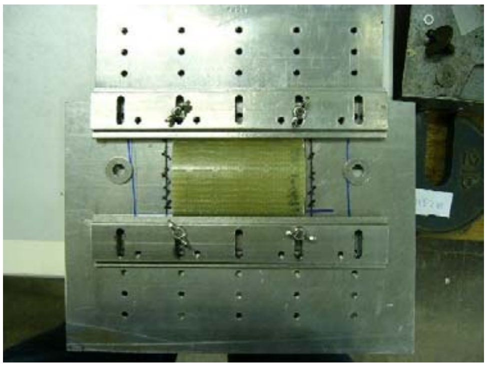

Figure 3 The clamping arrangment used for impact testing curved samples

5. COMPRESSION AFTER IMPACT TESTS

The compression part of the test consisted of supporting the plate vertically in an anti-buckling guide. In the QMW CAI rig the specimen rests in a slot at the bottom of the fixture and is supported by side anti-buckling guide. A top-loading fixture is also equipped with a slot to accommodate the plate, Figure 4. The fixture is adjustable to accommodate variable plane thickness. The same amount of support is offered to each specimen, independent of specimen width. The side anti-buckling guides are adjusted to grip the plate enough to restrain the buckling. The plate is however able to expand laterally.

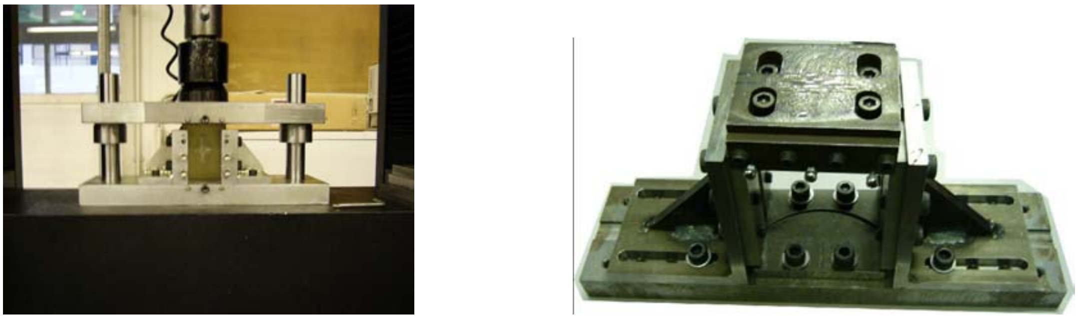

Figure 4. The QMW miniaturised CAI fixture and a modified fixture with an adjustable bottom slot for curved samples.

For the small curved panel, the rigs for the miniaturizing curved panel CAI test were modified to accommodate a curved slot for the specimen in the bottom of the rig and in the top loading plate. The fixture is adjustable to accommodate variable plane thickness. The side anti-buckling guides are adjusted to grip the plate enough to restrain the buckling. The plate is however able to expand laterally. A similar fixture was developed for the large curved specimens. A cross head speed of 0.5 mm/min was used for all the compression tests so as to achieve failure in 3~4min.

6. RESULTS

After impact testing the specimens, the apparent damage area and width was measured by taking photographs for glass fibre composites and using C-scan for the carbon fibre laminates. The damage width was based on the superposition of delamination between all plies in the laminate and is therefore a measure of the general extent of the damage, not a specific measure of size of any one delamination. The results of relationship between impact energy and width for glass and carbon fibre reinforced composite are shown in Fig 5.

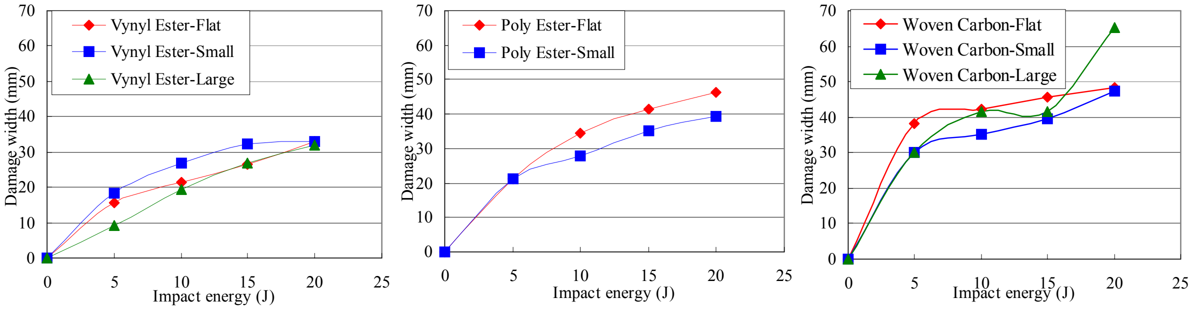

Fig 5. Impact energy versus Damage width of Vinyl Ester/ELT566 (left), Poly Ester/ELT566 (middle) and Vinyl Ester/Woven Carbon (right)

The results of compression after impact tests on QMW size flat glass fibre specimens, are presented in figure 6 with compression strength plotted against impact energy. The plot compares laminates with two different resin systems: the relatively tough 9102-500(Vinyl ester) and more brittle 489PA(Polyester), tested at four different impact energies: 5, 10, 15 and 20J. The residual compression strengths of the polyester resin system are lower than vinylester resin system.

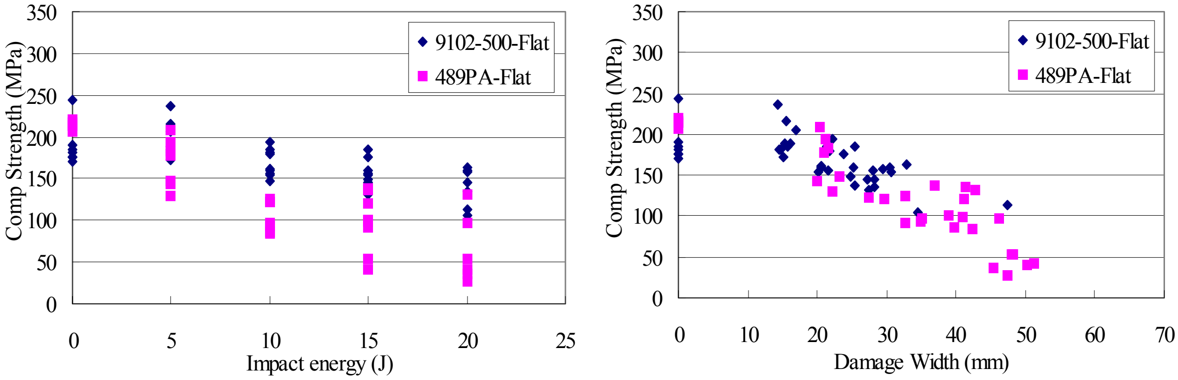

Fig 6. Impact energy and damage width versus compression strength of flat polyester and vinyl ester glass fibre laminates

When the data is plotted as compression strength versus impact damage width, the two data sets superimpose, although the range of damage formed in the polyester laminates is much greater than that generated in the vinyl ester laminates.

A similar comparison between the results of compression after impact tests on small curved-shape specimens, for the same two materials is shown in figure 7. In this case a clear difference was observed between the two data sets when using impact energy to compare the compression strengths, but only over the low impact energy range. The data sets converged at the higher impact energies. The plot comparing strength on the basis of damage width shows a similar trend to the flat plate specimens with both data sets overlapping. However, unlike the flat plates the range of damage widths is similar. This suggests that in the curved sample the damage has saturated the specimen at a much lower energy and this explains why the results for both materials are equivalent at the higher energy levels irrespective of the comparator used.

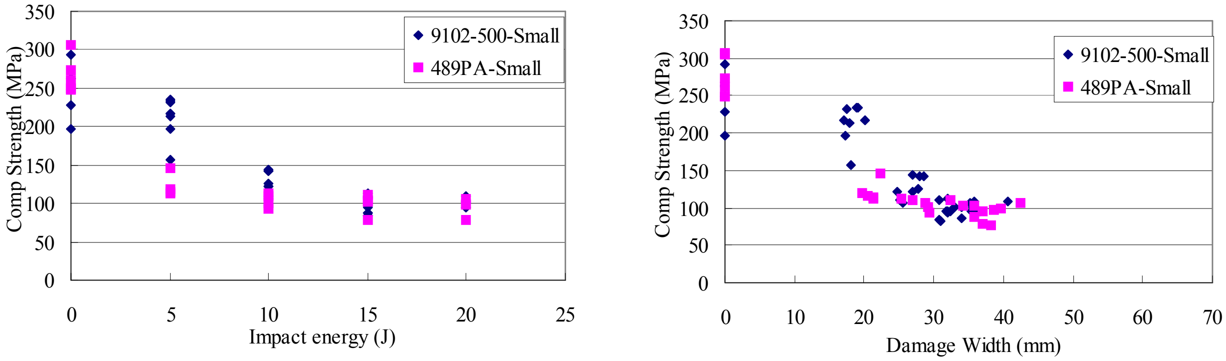

Fig 7. Impact energy and damage width versus compression strength of small curved polyester and vinyl ester glass fibre laminates

The results of compression after impact test for flat and small-curved shape specimens of CFRP, is presented in the same manner as the glass/resin panels, Fig 8. The initial observation was that the small curved samples possessed slightly lower initial compression strengths than the flat samples. For the QMW flat panels, the compression strength of specimens decreased rapidly with increasing impact energy, until a limiting value of 15J when the specimen was saturated (damage had extended to the extremities of the specimen.

The small curved specimens exhibited a more gradual reduction in the compression strength. The result of plotting compression strength against damage width is also shown in figure 8. It is difficult to identify the trends in this situation. Most data from the two sets of samples will superimpose over the damage width range 30-50 mm. However if the data is extrapolated back to the initial starting values of compression strength, then two different trend lines would be apparent with the flat specimens exhibiting a steeper and more serious reduction in compression strength with delamination size.

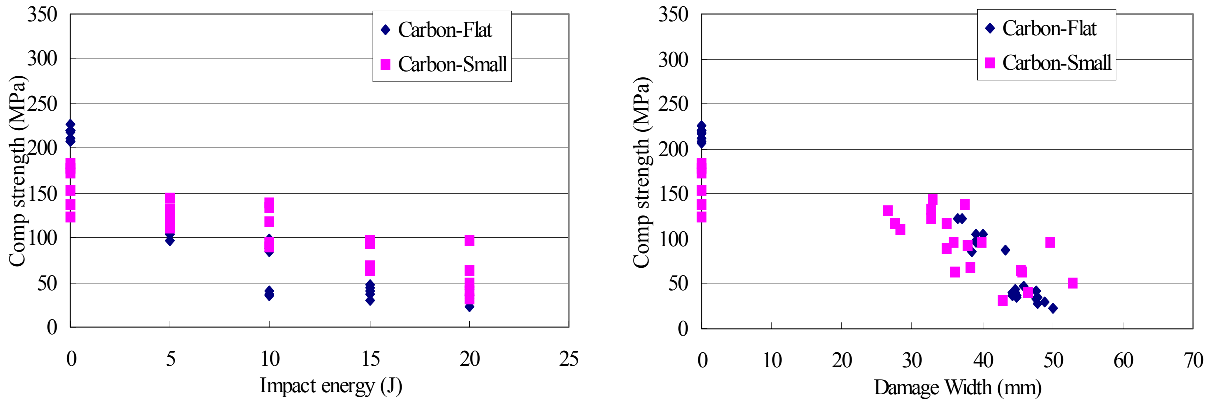

Fig 8. Impact energy and damage width versus compression strength of flat and small curved carbon fibre laminates

Figure 9 compares the results of compression testing on small-curved and large curved specimens of CFRP. In the impact energy versus compression strength graph, the small specimens exhibited higher strengths, but when the data is plotted against damage width the two data sets are very similar.

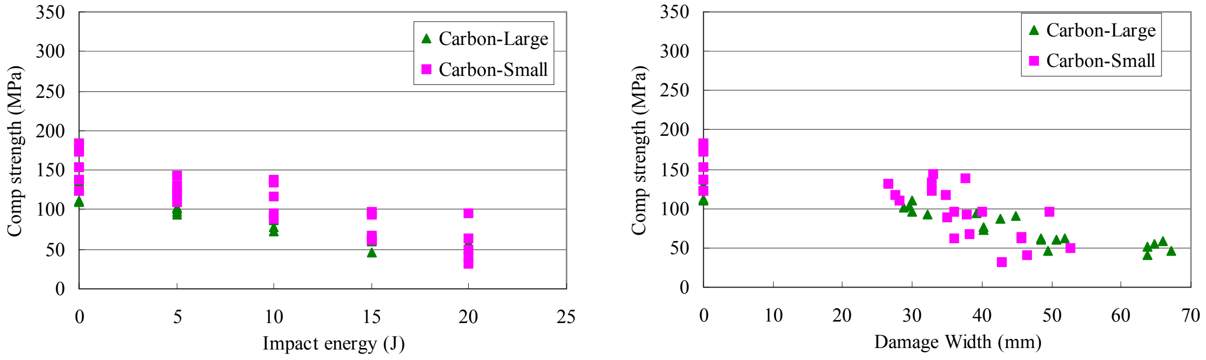

Fig 9. Impact energy and damage width versus compression Strength of large and small curved carbon fibre laminates

Figure 10 compares the flat specimens of glass fibre composite and carbon fibre composites. Both materials had a similar initial undamaged compression strength but the compression strength of the carbon fibre composite was lower than glass fibre composite after equivalent impact blows. The damage width versus compression strength graph shows that both data sets overlap.

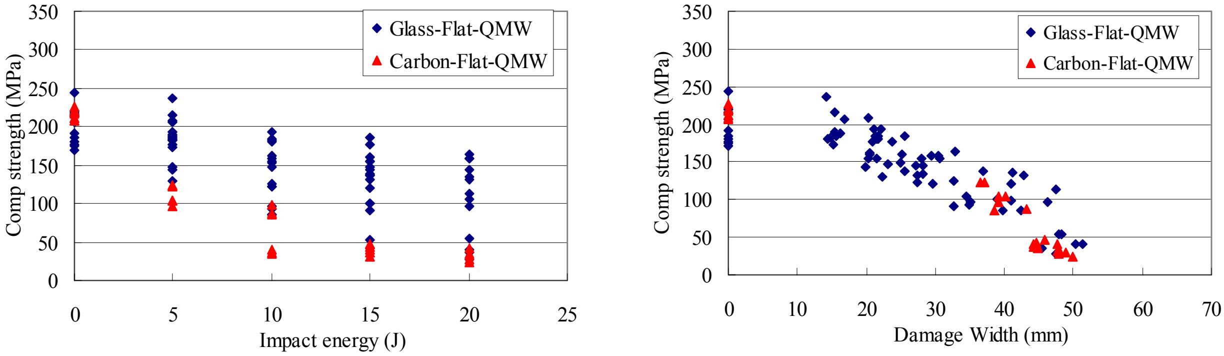

Fig 10. Impact energy and damage width versus compression strength of flat glass and carbon laminates

Figure 11 compares the compression strengths of the small curved specimens of glass fibre and carbon fibre. In these plots the behaviour of the two systems is different for both impact energy and damage width. The glass fibre specimens saturate with a residual compression strength of 100 MPa whereas the carbon specimens continue to show a reduction in strength to approximately 50 MPa. The comparison of the glass and carbon large scale curved specimens in figure 12 shows a similar trend.

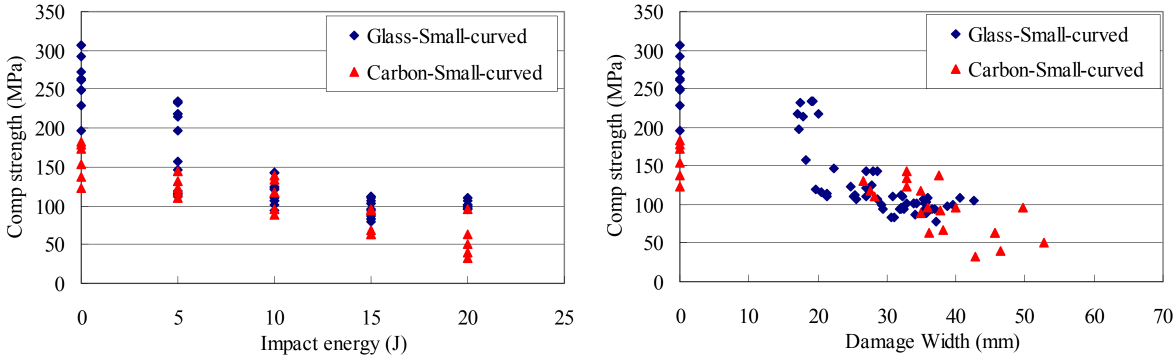

Fig 11. Impact energy and damage width versus compression strength, glass and carbon small curved specimens

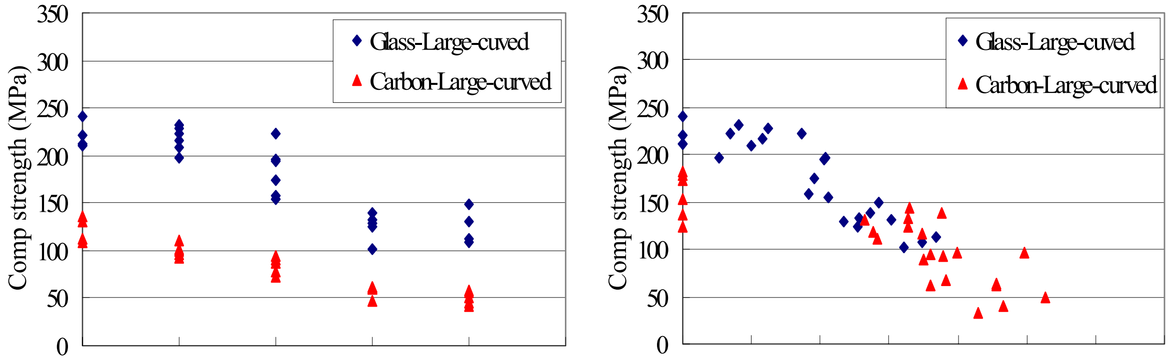

Fig 12. Impact energy and damage width versus compression strength of glass and carbon large curved specimens

The separation between the carbon and glass data sets is more pronounced when plotted against impact energy, but once again, the glass fibres specimens seems to exhibit a minimum compression strength of approximately 100 MPa while the carbon laminates continue to fall to a minimum of 50 MPa. The size of the largest damage area for the large curved glass fibre specimens was however relatively small and it is conceivable that impact blows of greater magnitude would induce a larger damage area that could further reduce the compression strength.

7. DISCUSSION

This programme was undertaken to determine the suitability of curved specimens as a tool fro the evaluation of damage tolerance via compression after impact testing. The first key finding concerns the utility of the curved specimens to distinguish between different laminate systems. The differences observed between flat plates produced from glass fibre composites with two resins, one of which was very tough, is mirrored in the results of the curved samples. This suggests that the curved specimen would be suitable for a materials evaluation programme.

The second is that unlike flat specimens, the curved specimens seem to fall to a minimum plateau value of compression strength, when the data is plotted against impact damage. Flat specimens in contrast do not exhibit such a trend and exhibit relatively linear relationship between damage width and compression strength exists right up to the point of saturation of the specimen, taken as the point that the width of the damage matches the unsupported width of the specimen. This change in behaviour may reflect the different sensitivity of the curved specimens to delamination damage.

The third key point is that the trends observed for the full scale large curved specimens are reproduced by the small scale curved specimens. This is encouraging as it suggests that a small scale miniaturised curved sample may provide all of the information required to complement that generated by miniaturised flat samples, as part of a comprehensive study of the damage tolerance characteristics of a particular composite material.

8. CONCLUSIONS

The miniaturised curved compression after impact test produces similar data to the large curved test, first used by Davies et al (6).

There are strong indications that the trends in the results for curved samples differ compared to flat plate samples under equivalent conditions.

9. ACKNOWLEDGEMENTS

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