DAMAGE TOLERANCE OF HIGH PERFORMANCE CONTINUOUS/DISCONTINUOUS HYBRID CARBON FIBRE COMPOSITES

Anthony D. Evans*, Lee T. Harper, Thomas A. Turner and Nicholas A. Warrior

Composites Research Group, Faculty of Engineering, University of Nottingham, NG7 2GX, UK
Email: Anthony.Evans@nottingham.ac.uk

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Abstract
Co-compression moulding of discontinuous fibre compounds (DFC) with modest amounts of continuous fibres (<20%.vol) to create hybrid laminates has been shown to enhance stiffness and strength by over 60% and 110% respectively compared with monolithic discontinuous fibre architectures [1]. This paper investigates the damage tolerance of a range of different compression moulded hybrid architectures by varying the through-thickness position of the continuous plies. By using drop weight impact tests at two impact energies (4.7J/mm and 6.7J/mm) and compression after impact (CAI), it has been shown that including 50% (by volume) of discontinuous fibres in an otherwise continuous laminate increases the retained compressive strength by up to 20% in comparison to a cross-ply laminate.

NDT and microscopy methods have been used to investigate the failure modes of the hybrid laminates. Non-planar crack propagation was observed post-impact in the discontinuous material as a result of the multi-directional architecture and the inherent stress concentrations at the fibre bundle ends [2]. Planar inter-ply delaminations were observed within the damaged continuous laminates. However, the hybrid laminates exhibit a mixture of these mechanisms, deflecting cracks around fibre bundles and away from the continuous-discontinuous fibre interface between the two materials and therefore reduces the linearity of the crack growth.

1. Introduction

A Directed Fibre Compounding (DFC) process has been developed to produce discontinuous carbon fibre epoxy moulding compounds suitable for compression moulding, with the potential for high levels of in-mould flow and tailored fibre architectures [3]. Using a robot arm, DFC simultaneously chops carbon fibre tows and sprays epoxy resin to impregnate the fibre bundles, using the constituent materials in their cheapest form. This has been shown to deliver a cycle time of less than 5 minutes for the production of components with complex geometries and features [1, 3]. This low-cost material has similar properties to more expensive, prepreg-derived carbon fibre / epoxy moulding compounds [4, 5]. The spray deposition approach has also been combined with preformed Non-Crimp Fabrics (NCF) to produce compression moulded hybrid structures [1] with the objective of high manufacturing rates and relatively low production costs compared to prepregs. DFC and impregnated NCF can be co-compression moulded, offering a rapid manufacturing route for producing structural automotive components from thermoset matrices.

Whilst positioning continuous fibre plies at the laminate surface enhances the bending performance in the longitudinal fibre direction, plies aligned in the primary load direction are typically positioned sub-surface to mitigate the risk of impact damage [6, 7]. However, multi-directional discontinuous fibre architectures reduce the notch sensitivity by distributing applied loads around damaged regions by means of adjacent fibre bundles orientated off the load axis [2, 8, 9]. Qian et al. [2] demonstrated that open-hole tensile specimens manufactured from discontinuous carbon fibre preforms can fail away from the notch. This is because of the high stress concentrations that form at the ends of fibre bundles relative to the stress concentrations that result around the open-hole.

Compression after impact (CAI) testing is commonly used to investigate the performance retention of composite laminates for aerospace components after a low velocity impact [10]. Out-of-plane impacts typically cause inter-ply delaminations, which significantly reduce interlaminar shear strength, tensile and compressive stiffness and strength [11]. Work by Kirupanantham [12] investigated the damage tolerance of short carbon fibre composites (<4mm) subjected to low velocity impacts, which showed that the damage mechanism was quite different to the continuous fibre materials. Discontinuous materials exhibit a fibre bridging effect between overlapping fibres to resist delamination. This was found to produce similar results to the bridging effect of through-thickness stitching yarns within NCF materials, significantly reducing the size of damage zones in comparison to UD architectures [12, 13]. This paper will therefore investigate the damage tolerance of compression moulded laminates consisting of hybrid fibre architectures, where the position of the continuous fibres is varied in relation to the discontinuous material in the through-thickness direction, to determine their influence on the post-impact compressive strength retention.

2. Experimental Procedure

2.1 Materials and moulding

Discontinuous fibre compound (DFC) was produced using the methodology outlined by Evans et al. [3]. A robot arm directed the deposition of chopped (25mm) Toray T700-50C 12K carbon fibre tows. Simultaneously, a spray cone of liquid epoxy resin converged with the fibres at the tool surface. The resin was then B-staged at room temperature to thicken the formulation to the desired moulding viscosity without the use of additives. The target fibre volume fraction for the charge was 50%. This compound was produced to a net-shape of 400mm × 400mm, ready for compression moulding. Unidirectional NCF, with an areal density of 375gsm, was impregnated using the same liquid resin and the same hardware as the DFC. This ensured that the cure reaction and crosslinking was consistent between dissimilar architectures. The target volume fraction for the continuous material was 60%. During the compression moulding, a constant closure speed of 1mm/s was used and the thickness of the laminate was controlled by the volume of material within the tool. This was then cured isothermally at 130ºC for 30 minutes at 85 bar.

Five laminate architectures were investigated: two monolithic (DFC and Cross-ply [$(0/90)_3$]s) and three hybrid architectures (namely *Centre* [DFC/$(0/90)_2$]s, *Interspersed* [DFC/$(0/90)_2$/DFC]s and *Surface* [$(0/90)_2$/DFC]s). These are shown in ***Fig. 1***. Each hybrid specimen contained 50% UD material and 50% DFC material (by volume), varying the thickness of the DFC charges as a function of the to the stacking sequence.

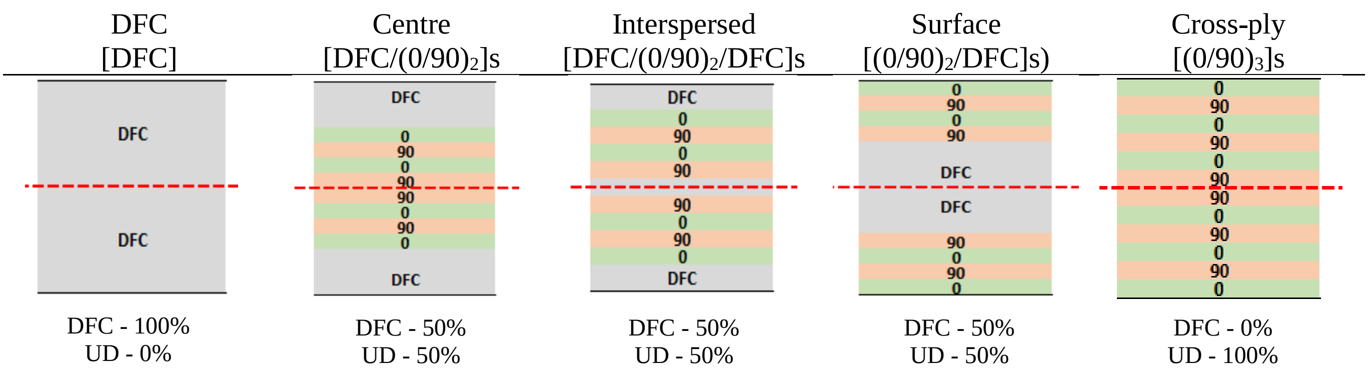


Figure 1. *Schematic diagrams of the monolithic and hybrid fibre architectures*

2.2 Test procedures

Initially, undamaged test coupons were evaluated by IITRI compression testing to establish the compressive stiffness and strength. These 150mm long specimens were 25mm wide for the DFC material to equal the fibre bundle length, and 15mm wide for the cross-ply and hybrid materials. A 12.7mm long region of interest was monitored via video extensometer to obtain the strain values. The test rate used was 1mm/min.

Impact specimens (150mm x 100mm) were cut from the plaques according to ***Fig. 2***. These were then subjected to an impact at the centre by a steel hemisphere within a falling-weight drop tower. The mass of the impactor was 8.641kg and the initial height of the dropped weight was governed by the thickness of each specimen to achieve impact energies of 4.5J/mm and 6.7J/mm. Six repeats were performed for each scenario.

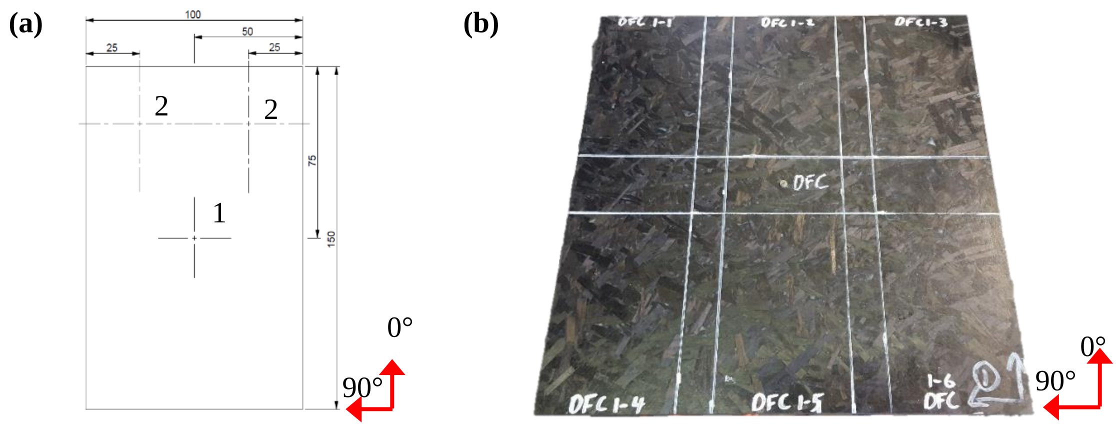


Figure 2. *Drop weight and CAI specimen dimensions with the position of the impactor, location 1, and the strain gauges, location 2, (a) and the plaque cutting plan (b)*

The impacted specimens were then further evaluated by non-destructive (NDT) and destructive testing. Ultrasonic C-scanning was performed to evaluate the size and shape of the damage zones. Two specimens for each scenario were also sectioned through the impact location to evaluate the damage sites by microscopy. The remaining four panels were then used for compression after impact (CAI) testing. A video extensometer was used to measure the compressive strains, but strain gauges (***Fig. 2a***) were also positioned on the front and back faces to indicate bending.

3. Results and Discussion

3.1 Drop-weight impact testing

The energy absorbed during impact was calculated with respect to time and normalised by the peak energy for each laminate type (***Fig. 3a***). The enery absorbed is determined by the plateu in the impact energy curve after the impact has been completed [14], which is summarised in ***Fig. 3b*** for the two impact energy levels studied. Although there was very little difference in the percentage of energy absorbed by the different architectures for the low impact energy (4.5J/mm), there was a large difference between the monolithic and hybrid structures at a higher impact energy (6.7J/mm). ***Fig. 3b*** shows that the DFC and cross-ply arrangements absorb approximately 27% of the applied high impact energy, whereas the hybrid specimens typically absorb about 10-13%. This suggests that there is a change in the scale or quantity of the cracks formed as a result of combining the continuous and discontinuous material, which will be investigated by the microscopy.

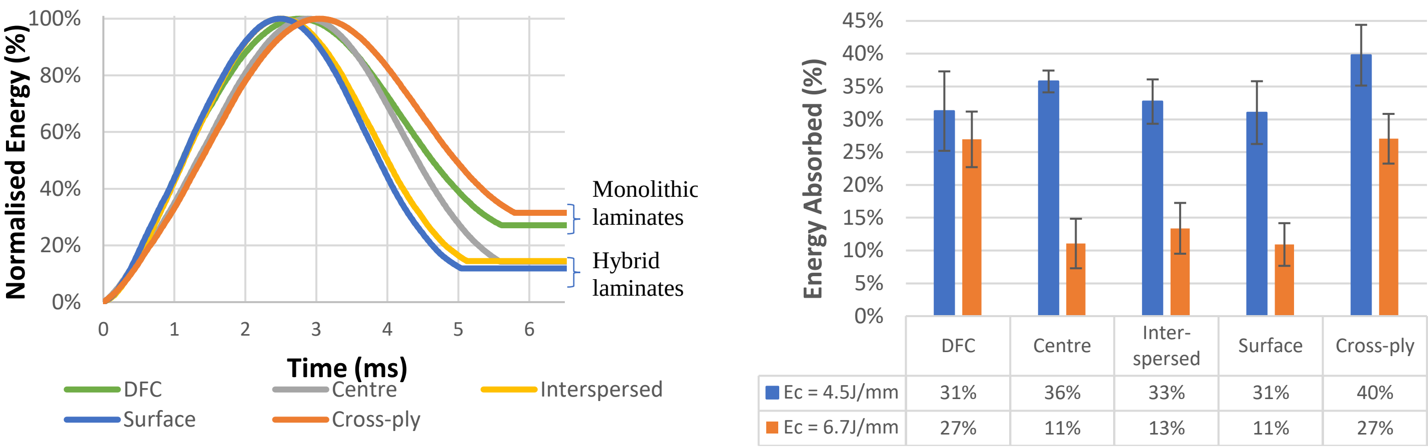


Figure 3. *Typical impact energies with respects to time during a 6.7J/mm impact, normalised by dividing by the peak impact energy of each impact (a). Selected examples are the closest results to average results shown in (b).*

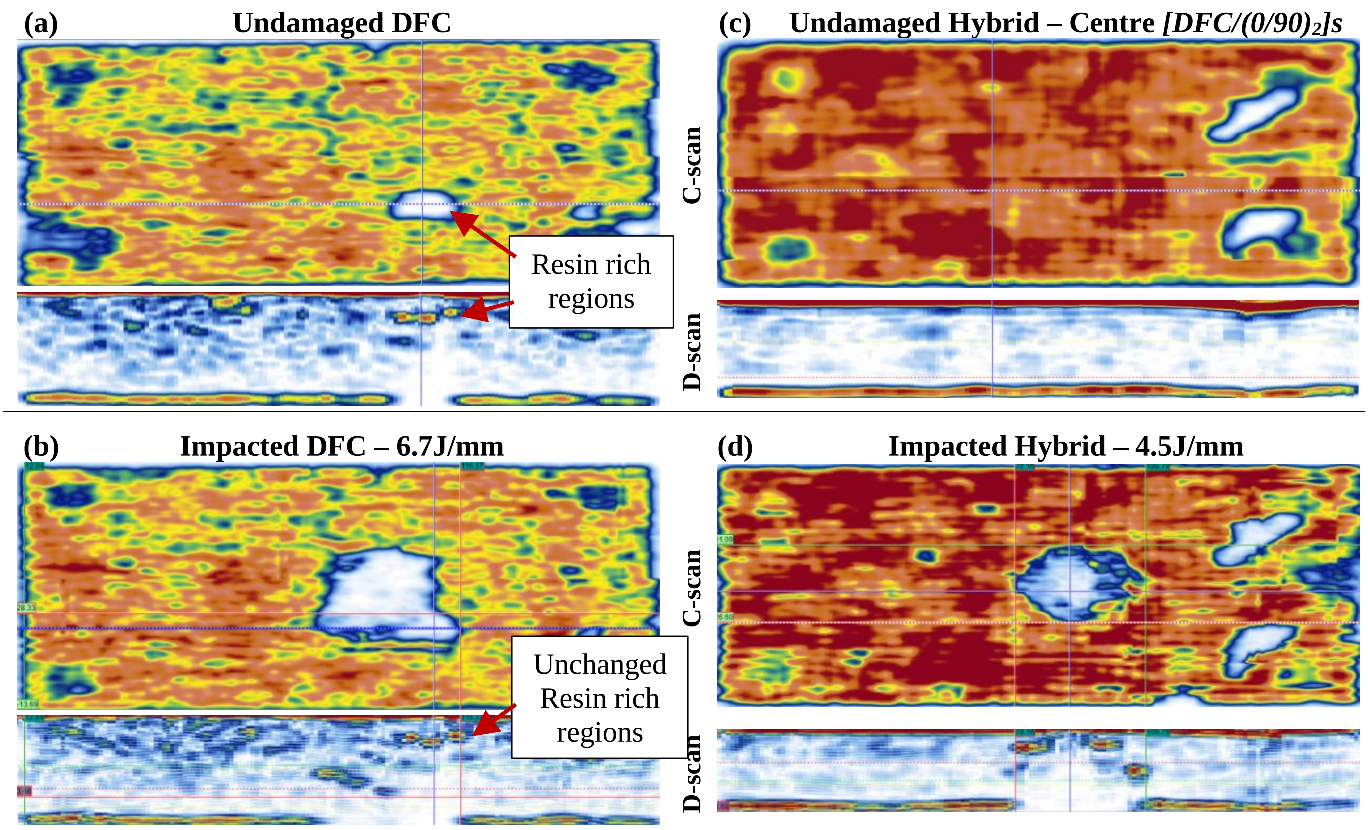


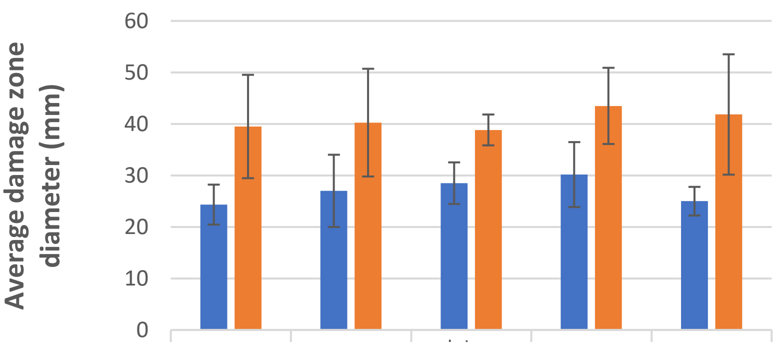
Figure 4. *Ultrasonic C-scans and D-scans of a DFC specimen: (a) undamaged and (b) impacted (Ec = 6.7J/mm), and of a Hybrid specimen (continuous material positioned at the centre): (c) undamaged and (d) impacted (Ec = 4.5J/mm).*

3.2 Damage zones

Ultrasonic C-scans were obtained before and after impact testing to visualise the size of the damage zones, in order to assess the influence of hybridising the fibre architectures. Images of the discontinuous DFC material exhibit a large variability in the amplitude of the return ultrasonic signal as a result of the random fibre bundle structure and resin regions. Reductions in signal amplitude occur near the corners, which are a result of the foam pads used to elevate the specimen. Some DFC panels contain large resin rich regions as a result of synchronised fibre bundle ends. This is seen in an undamaged DFC panel with a resin rich region located approximately 1mm below the surface, which is evident in the through-thickness D-scan (***Fig. 4a***). The difference in density between the fibres and resin causes the ultrasound to reflect at the boundary of the resin rich region, which obscures anything beneath. Coincidentally, this resin rich region was then close to the damage zone following impact, however the D-scans show that this region remains visibly unchanged post impact (***Fig. 4b***). This ultimately resulted in difficulties in quantifying the size of the damage zone of discontinuous fibre composites. Despite this defect however, there appears to be no significant difference between CAI strength of this specimen and the other specimens in this batch.

More uniform C-scans were observed following the introduction of continuous fibre plies to the DFC material to create a hybrid (***Fig. 4c***), regardless of the through thickness position of the UD plies. This contrast enables the damage zones to be clearly distinguished in the C-scan (***Fig. 4d***). However, the resolution of the scans did not provide a clear distinction in the through-thickness between the different fibre architectures from the D-scans alone.

Fig. 4b and ***Fig. 4d*** also demonstrate that the shape of the C-scanned damage zones were found to be irregular, with no distinguishable difference between each of the architectures investigated. The damage zones have therefore been considered to be approximately circular, enabling the diameter to be determined with regards to the length and width for each fibre arrangement. The average damage length and width were measured to the nearest millimetre from the four scans and are reported in ***Fig. 5*** as a damage zone diameter. There was a large degree of variability in the recorded damage zone sizes, but trends are distinguishable. Damage zones caused by low impact energy appear to increase in size as the UD plies are moved closer to the surface of the hybrid plaques: from ‘Centre’ to ‘Intersperse’ to ‘Surface’ (see ***Fig. 1***). However, there was no significant difference between damage zone size at the higher impact energy.



	DFC	Centre	Inter-spersed	Surface	Cross-ply
Ec = 4.5J/mm	24.33	27.00	28.50	30.17	25.00
Ec = 6.7J/mm	39.50	40.25	38.83	43.50	41.83

Figure 5. *Average damage zone diameters determined by the length and width of damage zones measured from each C-scan*

Micrographs taken through the impact zones (***Fig. 6***) indicate large amounts of delamination between the continuous plies, while shorter cracks form along the length of the discontinuous fibre bundles. Looking at internal damage in the cross-ply architecture, the longitudinal plies show delamination along the interface in the fibre direction. However, transverse fibres (orientated normal to the plane of the image) indicate that cracks propagate in the through-thickness direction of the ply, connecting the delamination sites either side of the transverse ply. Within the discontinuous DFC material there appears to be some planar delamination within fibre bundles. The lengths of these sites are therefore restricted to the length of the bundle itself, so the crack is quickly arrested or deflected around neighbouring fibre bundles. This crack deflection is also seen in the hybrid architecture, propagating cracks away from the large continuous interfaces. Therefore, despite the NDT testing being unable to detect a change in damage zone size, micrographs show that the path of the cracks do influence the level of damage absorption (***Fig. 3***).

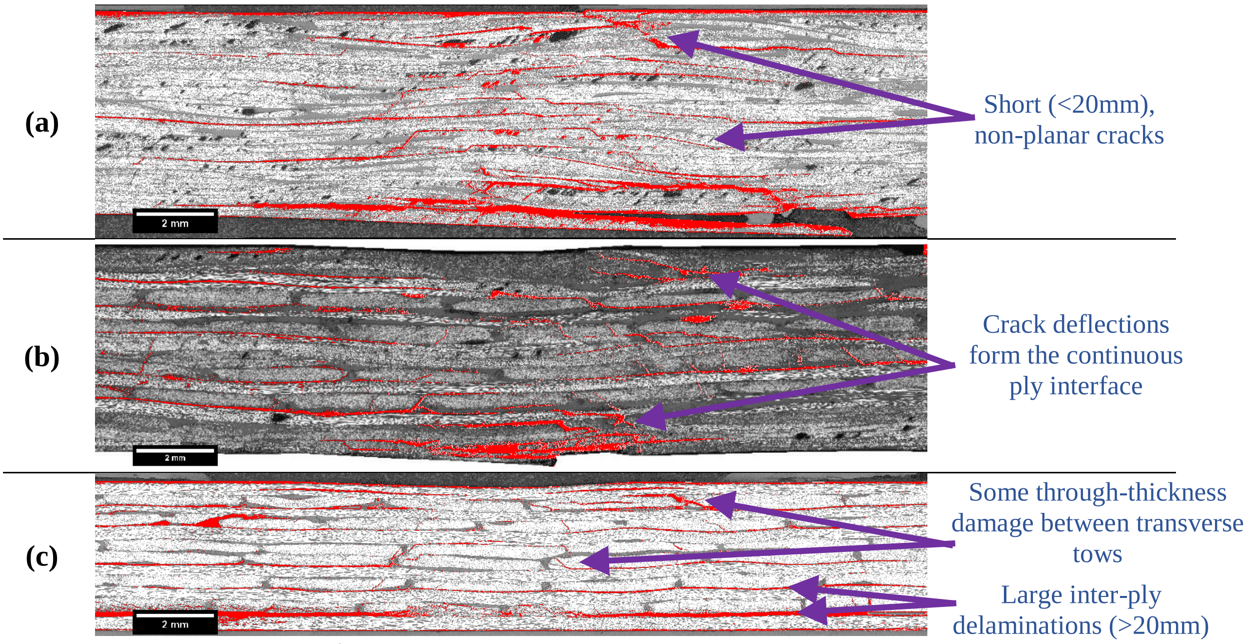
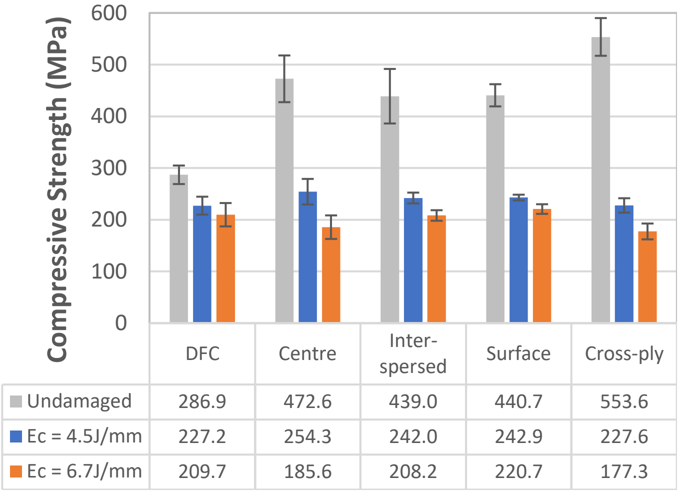


Figure 6. *Micrographs of impacted specimens with a threshold applied to show damage (Jc = 6.7J/mm). (a) DFC specimen, (b) Hybrid with NCF plies Intersperse and (c) Cross-ply. The middle of the image is aligned with the out-of-plane impact location.*

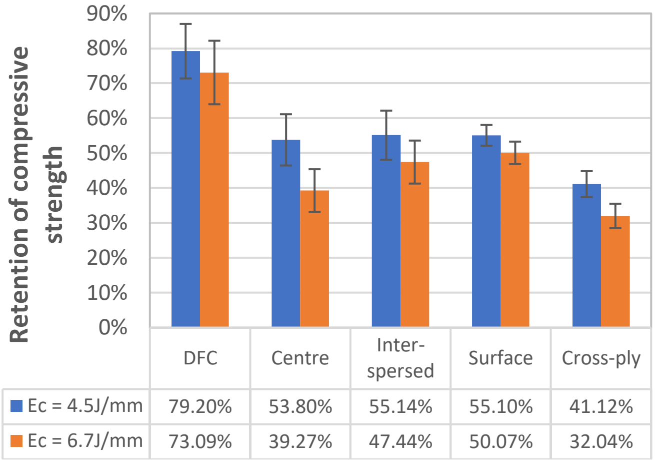
3.3 Compression after impact

The compressive strength after low energy impact is approximately the same (242-254MPa) for all hybrid architectures, regardless of their undamaged compressive performance (***Fig. 7a***). The damage tolerance of the hybrid panels at a low impact energy appears insensitive to the thickness of the DFC skins. This however may be the result of material variability, or the thickness of the DFC skins needs to be greater to have a measurable difference. The highest strength retention following impact is observed for the discontinuous architecture at 79%, compared with just 41% for the Cross-ply architecture (***Fig. 7b***). Increasing the impact energy to 6.7J/mm reduced the strength retention further. The compressive strength of the Cross-ply reduced by a further 50MPa to 177 MPa (32% retention) and the DFC by just 20MPa to 210 MPa (73% retention). The post-impact compressive strength of the DFC was therefore higher than the post impact strength of the Cross-ply architecture (following a 6.7J/mm impact).

When considering the hybrid architectures, there was no distinguishable difference in the compressive strength and percentage strength retained for the hybrid fibre architectures, following the low energy impact. These specimens retained 53-55% of their compressive strength post impact. After increasing the impact energy, it was found that there was no difference between the compressive strength retained by the Surface and Intersperse fibre arrangements, whereas the compressive strength of the Centre arrangement retained approximately 10% less. This indicates that the dominating factor between the impact behaviour of these hybrid architectures is the thickness of the continuous region. Intersperse and Surface arrangements contain stacks of 4 plies through the thickness separated by DFC material, whereas positioning the continuous plies at the centre creates a singular 8 ply stack with DFC skins. Thicker laminates exhibit larger delaminations during the absorption of impact energy [14, 15]. Therefore, by increasing the number of continuous plies within a stack (uninterupted by DFC) the scale of the damage zone increases as a result of lower damage resistance compared to thinner ply stacks [16, 17].



(a)



(b)

Figure 14. *Compressive strengths of each fibre architecture prior to impact testing and after exhibiting target out-of-plane impacts of 4.5J/mm and 6.7J/mm (a) and the percentage of retained compressive strength for each impact (b)*

4. Conclusions

Positioning primary load carrying plies the centre of the composite (through-thickness) improves the damage tolerance of the structure by using discontinuous fibres to protect the load carrying plies during an impact [6, 7]. Hybridising the fibre architecture by introducing discontinuous fibres improved the damage tolerance of the laminate, retaining approximately a 20% higher compressive strength compared with Cross-ply structures when subjected to a high impact energy, 6.7J/mm. However, results indicate that hybrid architectures containing continuous ply stacks positioned at the surface or architectures interspersed with DFC, retained the highest compressive strength post-impact (approximately 50% after an impact energy of 6.7J/mm). Positioning the continuous ply stack near the centre of the laminate to maximise the thickness of the DFC skins, retained only 39% compressive strength after a 6.7J/mm impact. This can be partially attributed to the different damage mechanisms for discontinuous and continuous fibre materials. There are short, non-linear cracks visible within the discontinuous architecture and long, linear delaminations exhibited between the continuous plies. Therefore, stacking 8 continuous UD plies together is increasingly likely to increase delamination around the primarily loaded longitudinal plies than by dividing into two 4 ply stacks with greater ability to transfer energy into the multi-directional fibre bundles. It is widely known that thinner plies exhibit greater damage resistance and exhibit smaller damage zones than thick plies [14-16]. Microcracks form at lower strains within the matrix of transverse lamina of greater thickness. Within the hybrid arrangements, the number of consecutive continuous plies between DFC material has a significant influence over the damage resistance, even though equal in-plane stiffness, total thickness and continuous-discontinuous material ratios (by volume) are maintained. An additional influence of positioning the continuous plies at the centre would be an increase in ply waviness, due to being unconstrained by the tool surface. This would reduce the overall compressive performance further as a result of increased buckling, rather than improve the strength retention of impacted versus non-impacted specimen.

Acknowledgments

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