IMPACT RESISTANCE AND TOLERANCE OF INTERLEAVED RTM LAMINATES

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SUMMARY: This paper presents and discusses the results of low-velocity impact and compression-after-impact (CAI) tests conducted on interleaved and non-interleaved carbon/epoxy RTM laminates. The implementation of low modulus copolyamide web interleaves resulted in a negligible change in damage area and CAI behaviour. Examination of laminate cross sections revealed this was due to both the open structure of the interleaf and poor resin/interleaf adhesion. Olefin net interleaves were subsequently trialed, and provided a strong interface bond, resulting in a reduction in projected damage area. These interleaves changed the stress distribution under impact and restricted delamination formation at the ply interface. An investigation into the compression behaviour of these laminates revealed a reduction in undamaged strength using olefin interleaves. This was attributed to the lack of lateral support for fibres, allowing fibre microbuckling to occur at a low load.

KEYWORDS: interleaving, impact, compression after impact, resin transfer moulding

INTRODUCTION

The use of structural composites has been limited by their low impact resistance and damage tolerance properties. Much work has been conducted to address this problem, with various techniques developed including resin modification and 3D reinforcements. However, many of these techniques involve costly manufacturing processes or result in degradation of the mechanical properties of the composite. One method used to improve impact properties in prepreg laminates is the technique of interleaving, which involves the insertion of thin, tough, polymer layers (interleaves) between selected plies of the composite laminate. Various researchers have reported increases in impact resistance and damage tolerance, including Masters [1], Evans et. al. [2], Sun and Rechak [3] and Gandhe and Griffin [4]. In the current work, this technique has been applied to composites manufactured using the resin transfer moulding (RTM) process, incorporating porous thermoplastic interleaf materials.

Fig. 1(a) and 1(b) show cross sections of a non-interleaved (NI) and web-interleaved laminate respectively, with the interleaf shown as the dark areas at the interfaces in Fig. 1(b).

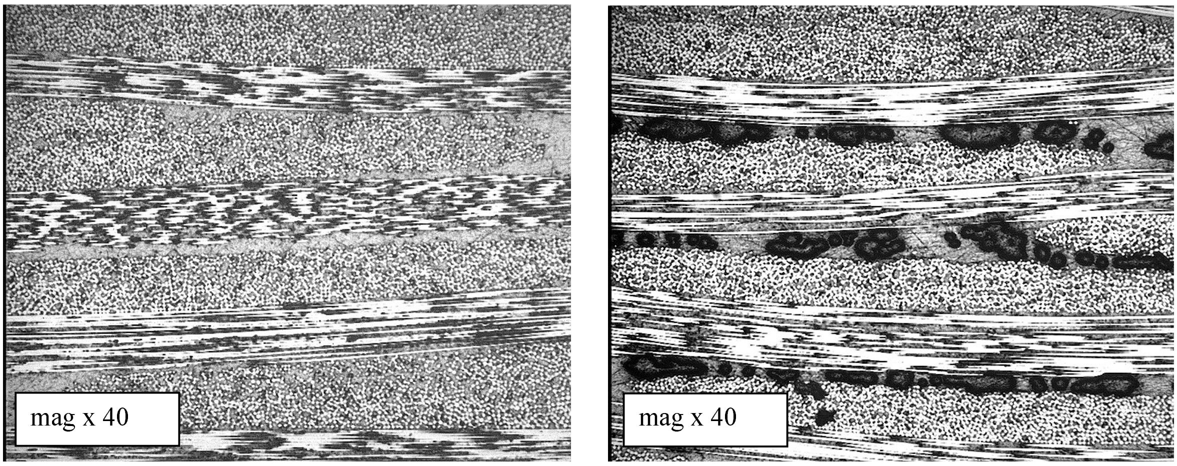

Figure 1(a) and 1(b): Non-interleaved and 1a8s18 interleaved laminate cross sections

TEST APPARATUS AND MATERIALS

Carbon/Epoxy RTM Specimens

All carbon/epoxy (C/E) laminates were manufactured using Araldite F epoxy resin (LY556/HY917/DY070) peripherally injected into a closed RTM mould at 200 kPa constant injection pressure, with full vacuum applied at the mould exit. The laminates were cured at 90 °C for 3 hours and post-cured at 145 °C for 4 hours.

Initially, uniweave carbon fabric (Brochier E3994) was used to manufacture 8 ply quasi-isotropic (QI) specimens $[(+45),(-45),(90),(0)]_S$. This was to provide a mismatch of properties between dissimilar orientation plies, increasing likelihood of delamination along these interfaces under impact loading. The interleaved specimens used a thermofusible copolyamide web (Protechnic 1a8s18) interleaf between dissimilar orientation fabric plies. These laminates were designated Group A.

Following initial testing and investigation into failure mechanisms, two thermofusible olefin nets (XIRO XAF2215 and XAF2085) were used as the interleaf material. Specimen layup followed the SACMA test specification for CAI [5], such that the non interleaved uniweave specimens used an 8 ply lay-up $[(+45),(0),(-45),(90)]_S$. Interleaved uniweave specimens had an interleaf between dissimilar orientation fabric plies such that the lay-up was $[(+45),I,(0),I,(-45),I,(90)]_S$, These laminates were designated Group B.

Following this, further investigation was conducted using plain weave (PW) fabric (Brochier GY926) and olefin nets (XAF2215 and XAF2085) as interleaf materials. The plain weave specimens used a 12 ply layup $[(\pm45),(0/90)]_{3S}$ as specified by the SACMA test specification for CAI, while the interleaved layup was $[(\pm45),I,(0/90),I,(\pm45),I,(0/90),I,(\pm45),I,(0/90)]_S$. These specimens were designated Group C.

Drop Weight Impact Tests

Low velocity impact tests were conducted following the CRC-ACS impact test specification [6], and using a drop weight test rig as shown in Fig. 2. The specimens measured 90x115 mm, and were machined with tolerances as designated by the specification. The specimens were clamped using an edge support frame with an impact window of 80x90 mm. The impactor used a hemispherical steel tup of diameter 12.5 mm and used variable weights and heights to impact the specimen at incident energies up to 7 J/mm. Following impact, the specimens were c-scanned to determine the projected damage area, with selected specimens sectioned and viewed under a microscope to investigate failure paths and mechanisms.

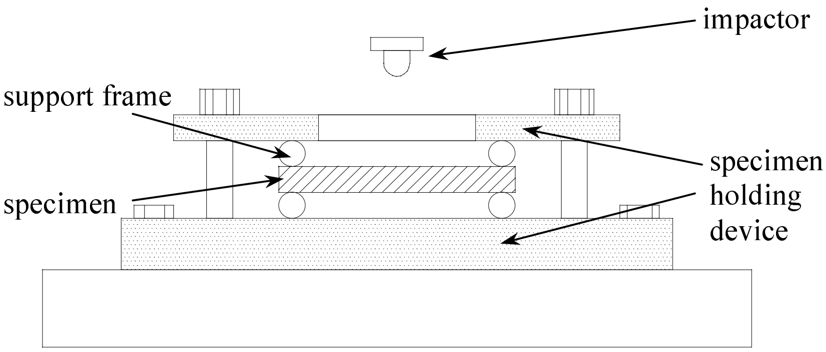

Figure 2: Schematic of drop weight impact test rig

Compression After Impact (CAI) Tests

Compression tests were conducted on impacted and non-impacted specimens using a modified rig developed at the CRC-ACS, and following the CRC-ACS CAI test specification [7]. The schematic of the rig is shown in Fig. 3. The CAI tests were conducted at a displacement rate of 0.5 mm/min and were concluded at the first onset of failure.

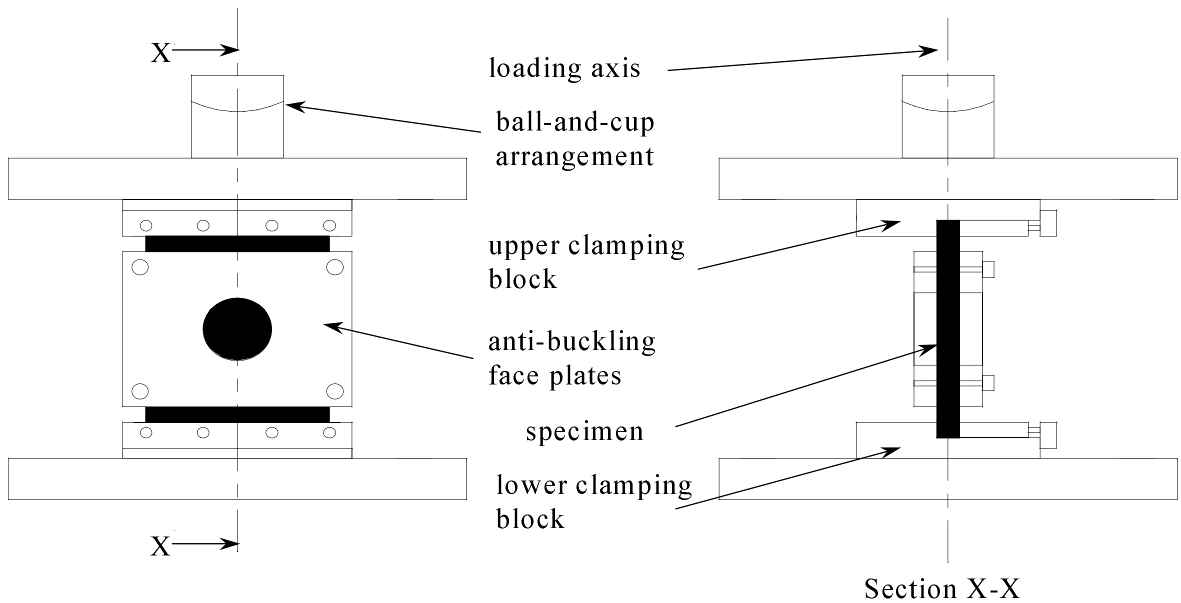

Figure 3: Schematic of CAI test rig

RESULTS

Low-velocity Impact of Quasi-Isotropic Specimens

As seen in Fig. 4, quasi-isotropic carbon/epoxy laminates (Group A) interleaved with the 1a8s18 copolyamide interleaf demonstrated no significant change in projected damage area. This suggested the interleaf had no effect on the stress distribution at the fibre-matrix interface, nor resisted transverse cracks or delaminations. As shown in Fig. 5(a), due to the interleaf having a very open web structure, cracks were able to propagate easily between the gaps in the thermoplastic. Another reason for the lack of delamination suppression was the poor bond between the copolyamide and the epoxy resin. Even though the thermoplastic was heated past its melting point during post-cure, the bond was very weak. This is seen in the crack propagation along the thermoplastic/epoxy interface in Fig. 5(b).

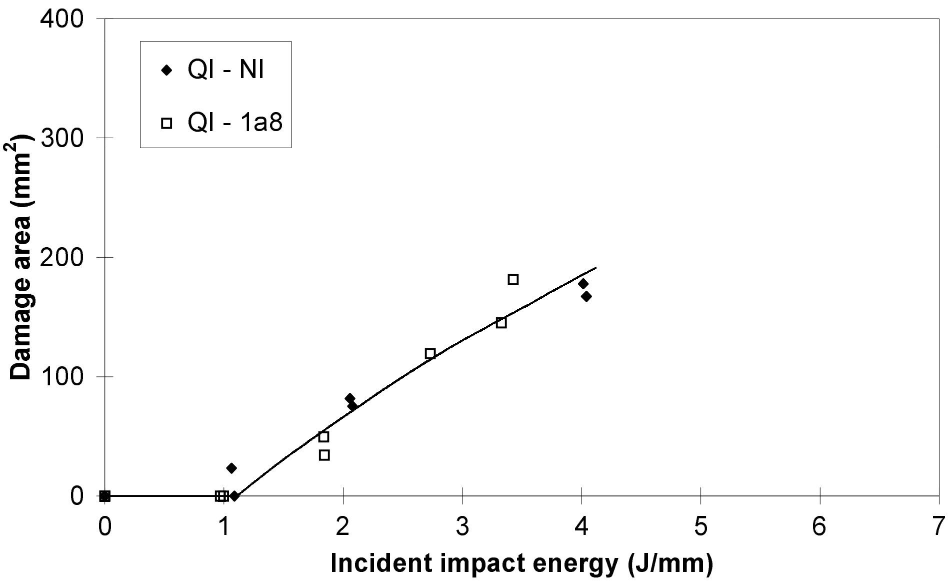

Figure 4: Damage Area (C/E-QI RTM: Group A)

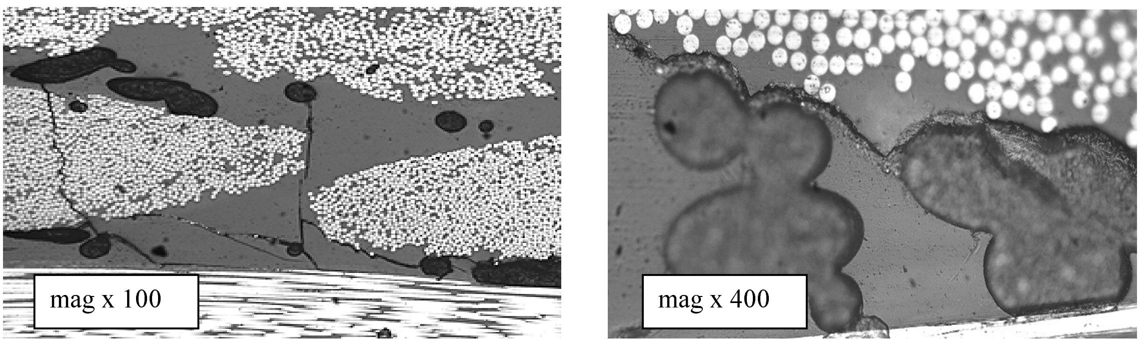

Figure 5(a) and (b): Delamination/transverse crack propagation (C/E-QI RTM: Group A)

This result led to the selection of another type of interleaf material; thermofusible olefin net, XAF2215 and XAF2085 (XAF2085 had more open area than XAF2215). These were used because the bond between the polyethylene based olefin and the epoxy resin was very strong. This was a result of the liquid polyethylene wetting solid epoxy very well, indicated by a low contact angle (θ), as illustrated in Fig. 6(a). This is compared to Fig. 6(b), which shows a high contact angle for liquid epoxy on solid polyethylene, ie: poor wetout. Therefore, the polyethylene based thermoplastic was heated past its melting point during post-cure to allow adequate adhesion to the epoxy matrix

Figure 6(a) & (b): Contact angle - liquid PE/solid epoxy & liquid epoxy/solid PE

The results of the impact tests for Group B are provided in Fig. 7. They show a marked decrease in projected damage area for the olefin interleaved laminates at similar impact levels, as well as a higher damage initiation impact energy. This increase in impact resistance is due to the ductile interleaf changing the formation and distribution of interlaminar stresses under impact. The interleaf forms a good bond with the epoxy resin, resisting transverse cracks from forming delaminations at the mismatched ply interfaces. This is shown in Fig. 8(a), compared with the unrestricted transverse crack/delamination formation in the non-interleaved laminate, Fig. 8(b). Another result of the change in stress distribution under impact is the increase in inclination angle of the transverse cracks. The angle is between 80 and 90 degrees in the interleaved laminate, as compared to around 45 degrees in the non-interleaved laminate. This increase in angle is an indication of a change in failure mode from shear to bending, using the different impact failure modes described by Sun and Rechak [3].

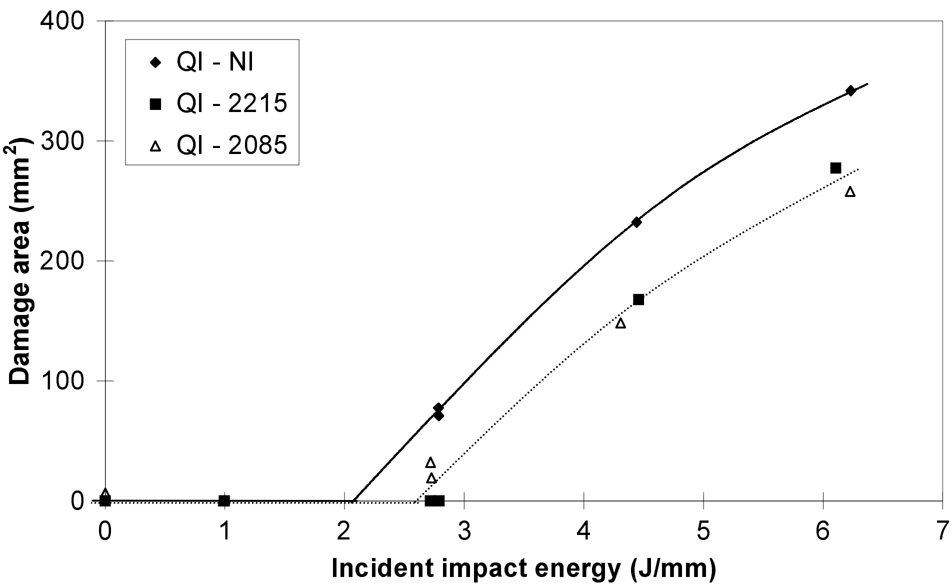

Figure 7: Damage Area (C/E-QI RTM: Group B)

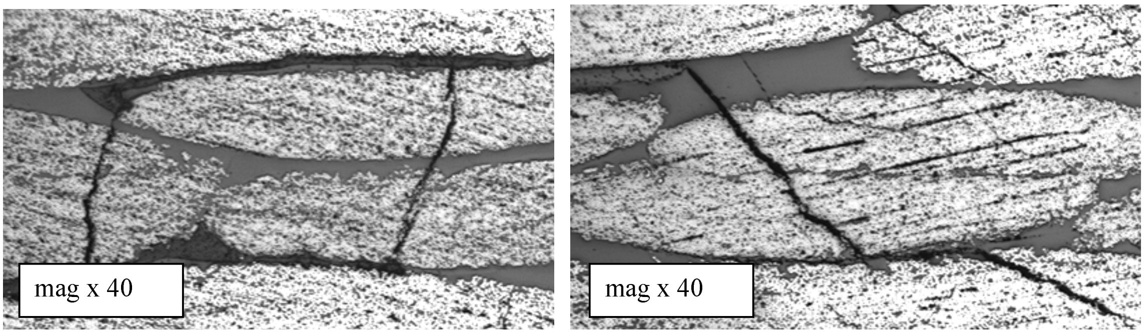

Figure 8(a) and (b): Transverse crack/delamination (C/E-QI RTM: Int-2215 and Non-int)

Low-Velocity Impact of Plain-Weave Specimens

Impact tests were also conducted on plain weave fabric carbon-epoxy specimens. The thermoplastic olefin materials were again investigated, with the results of these tests shown in Fig. 9. Although a moderate decrease in damage area was produced with XAF2215 and XAF2085 interleaves, this was more prominent at higher impact energies. Due to their architecture, woven fabrics are generally recognised as being more damage resistant than unidirectional materials. Hence, increases in damage resistance are not as easily achieved. This was also reported by Leong et. al. [8] in their work into increasing damage resistance of plain weave carbon/epoxy composites using through thickness stitching.

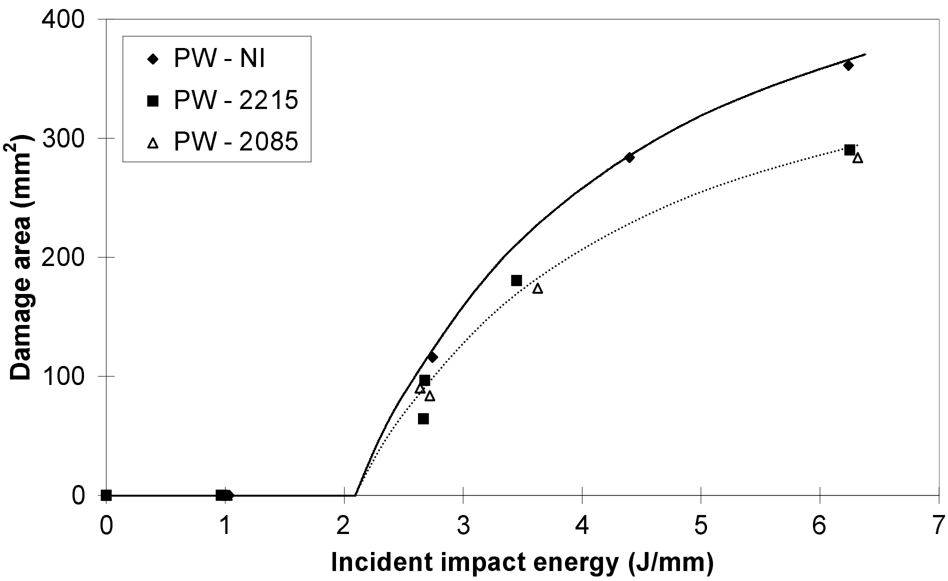

Figure 9: Damage Area (C/E-PW RTM: Group C)

Compression After Impact of Quasi-Isotropic Specimens

As shown in Fig. 10, no significant change in undamaged and damaged compression strength was evident using laminates interleaved with the open copolyamide web. This is because the web did not affect the properties of the interface resin layer or the lateral support for the fibres. Hence, the compression strength was a function of the damage area, which was the same for non-interleaved and 1a8s18 interleaved laminates.

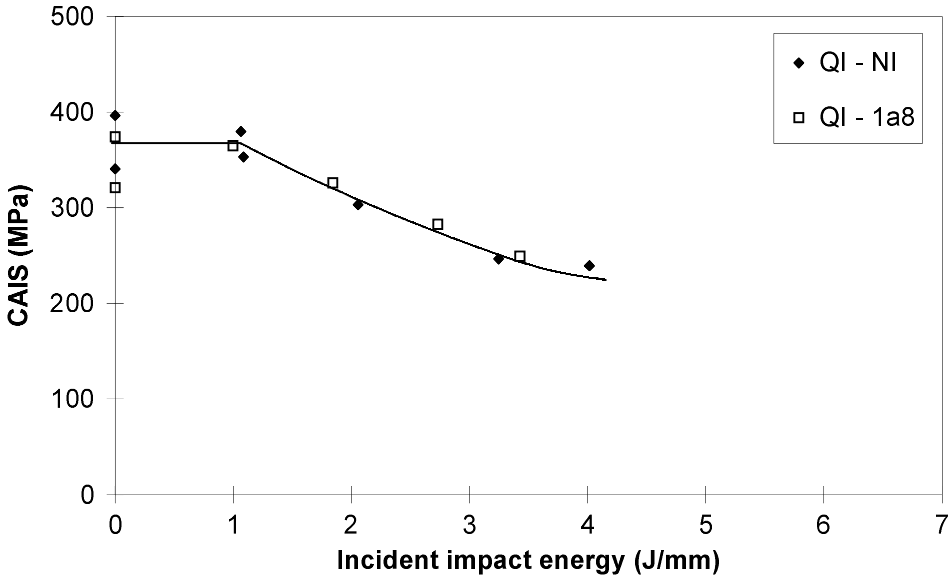

Figure 10: CAIS (C/E-QI RTM: Group A)

The XAF2215 and XAF2085 interleaves had a significant effect on the compression behaviour of quasi-isotropic uniweave laminates. As seen in Fig. 11, the undamaged compression strength was reduced by 45 and 30 percent respectively. The two types of olefin interleaf displayed similar behaviour, with the extent of reduction in compression strength dependent on the hole size of the net structure, ie open XAF2085 net resulted in a smaller decrease. It is worth noting that the interleaved compression strength was not reduced until an impact energy of nearly 3 J/mm, after which the XAF2085 interleaved specimens displayed very similar behaviour to the non-interleaved specimens. The cross section of a compressed 2215 interleaved specimen, presented below in Fig. 12, indicates the failure was due to out of plane microbuckling of the fibres followed by a form of kink band failure. This is not seen in the non-interleaved laminates and is attributed to the lack of lateral fibre support under compression with the olefin interleaf.

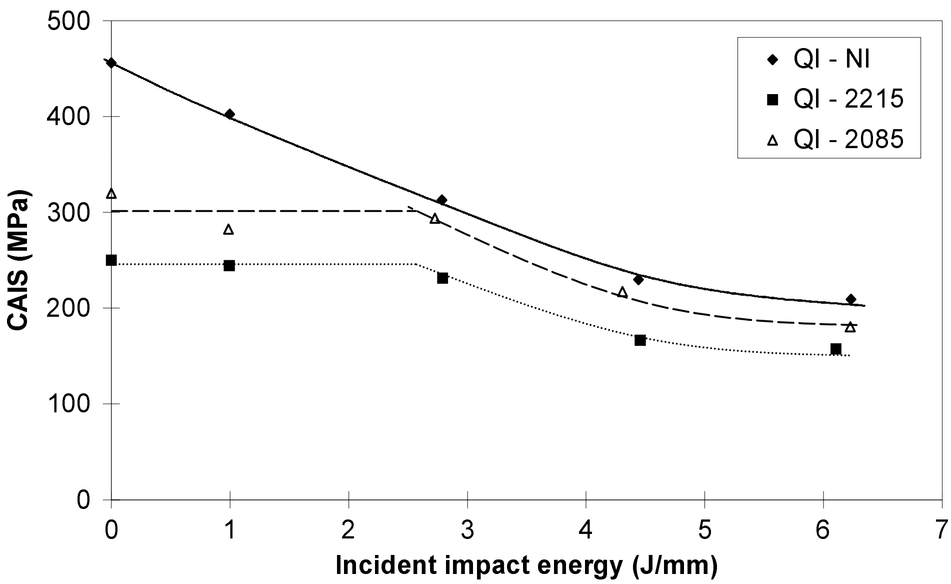

Figure 11: CAIS (C/E-QI RTM: Group B)

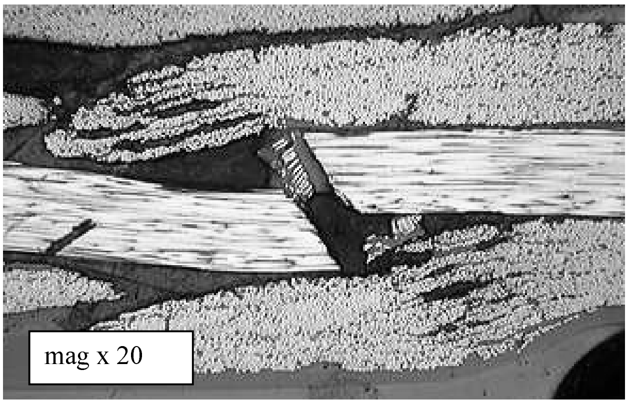

Figure 12: CAI cross section (C/E-QI RTM: Int-2215)

Compression After Impact of Plain Weave Specimens

The behaviour of the interleaved plain weave specimens under compression was similar to that of the interleaved uniweave specimens. The lack of out of plane support for the fibres allowed microbuckling to occur at relatively low loads, hence a significant reduction in undamaged compression strength. As shown in Fig. 13, the CAIS of the XAF2085 interleaved laminates tended towards the non-interleaved CAIS at around 4 J/mm, with the XAF2215 having a lower CAIS over the range of impact energies. As described by Evans and Masters [9], the shear modulus of the interleaf material and composite volume fraction are important parameters with regard to lateral support for the fibres and microbuckling under compression. Although this was with particular reference to film interleaves in prepreg laminates, it can be applied qualitatively for the current work. Therefore, the compression strength may be increased using a higher shear modulus thermoplastic interleaf, and is the subject of continuing research in this field.

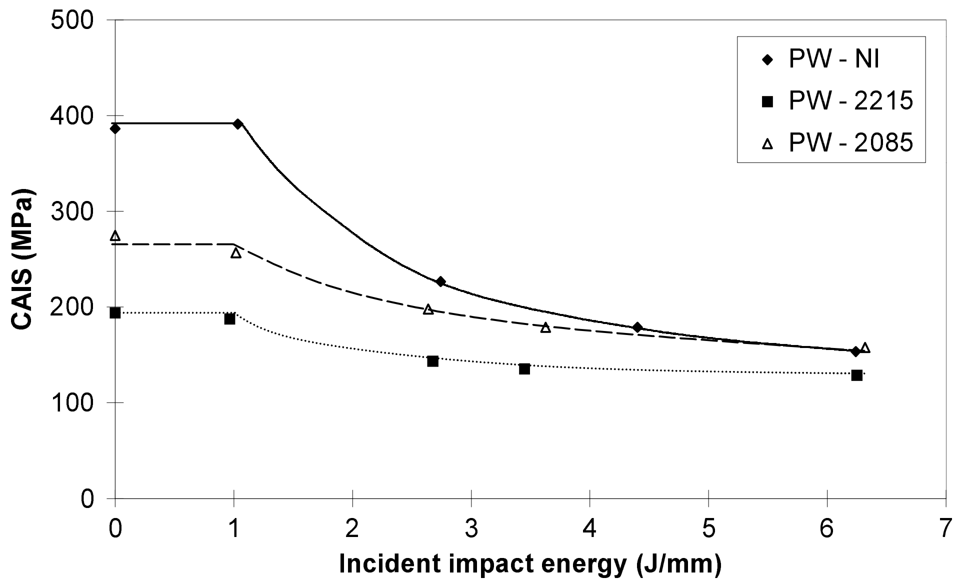

Figure 13: CAIS (C/E-PW RTM: Group C)

CONCLUSIONS

The two types of interleaf material investigated offer different property tailoring options for interleaved RTM composites. The copolyamide interleaf may be used to bond fabric plies together in RTM preform manufacture with no significant detrimental effect on impact and post-impact mechanical behaviour. The olefin interleaf increases impact resistance, shown by a decrease in projected damage area. However, this is accompanied by a reduction in compression strength due to a lack of lateral support for the fibres. This reduction in visible damage area may be of use in lightly or non-loaded non-structural components. However, for structural components, the compression strength may be improved using a higher shear modulus interleaf material, which is the subject of continuing research in this field.

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