The influence of toughening-particles in CFRPs on low velocity impact damage resistance performance

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Abstract

The role of particle-toughening for increasing impact damage resistance in carbon fibre reinforced polymer (CFRP) composites was investigated. Five carbon fibre reinforced systems consisting of four particle-toughened matrices and one system containing no toughening particles were subjected to low velocity impacts ranging from 25 J to 50 J to establish the impact damage resistance of each material system. Synchrotron radiation computed tomography (SRCT) enabled a novel approach for damage assessment and quantification. Toughening mechanisms were detected in the particle-toughened systems consisting of particle-resin debonding, crack-deflection and crack-bridging. Quantification of the bridging behaviour, increase in crack path length and roughness was undertaken. Out of the three toughening mechanisms measured, particle systems exhibited a larger extent of bridging suggesting a significant contribution of this toughening mechanism compared to the system with no particles.

Keywords: A. Carbon fibre; B. Impact behaviour; B. Fracture toughness; X-ray computed tomography

1 Introduction

Carbon fibre reinforced polymer (CFRP) composites are susceptible to impact damage. This is of particular concern in the case of barely visible impact damage (BVID) caused by low velocity, high mass impacts. In this case, macroscopically small dents may be generated on a composite laminate surface, overlaying significant internal damage, which is therefore problematic to detect by standard in service methods [1, 2]. Such internal damage typically consists of a network of intralaminar matrix cracks and interlaminar delaminations [3, 4], with fibre fracture occurring at the higher end of low velocity impact damage [2, 5-7]. Of the three damage modes mentioned, delaminations are widely accepted as being responsible for reduced residual compressive strength; wherein the delamination area is reported to

correlate with the loss in compression strength [8-10]. Delaminations may be considered to create sublaminates with lower in-plane load-carrying capabilities prior to buckling [11, 12]. It is therefore desirable to minimise the extent of delaminations by increasing the intrinsic damage resistance of the material. The extent of damage under low velocity impact is typically measured by ultrasonic C-scan which reveals a projected damage area representative of the scale of these delaminations [8]. However, this technique neglects the three-dimensionality and multiplicity of interacting damage modes.

Due to cost and processing considerations, composite materials commonly use thermoset resins that have relatively poor intrinsic impact toughness compared to thermoplastics [13]. The toughness of these resins can be improved by introducing second phase particles [14]. Ideally the associated increase in toughness should be directed to the interlaminar regions to reduce the extent of delaminations and thus increase the impact damage resistance of the material [15].

It has been widely reported that toughness improvements seen in neat resins (*i.e.* fibre-free monolithic samples) do not usually translate to equivalent improvements in composite intralaminar toughness [16-18]. This has been linked to the effective scale of the crack-tip process zone; in composite materials the interply region is constrained by the fibres, and the thickness of this region is usually much less than that of the process zone seen in bulk material [19, 20]. Studies which correlate the thickness of the resin-rich region with toughness show that toughness increases with thickness [20]. In terms of resin toughening strategies, an ancillary benefit of the widely used particle toughening approach is the creation of thickened resin-rich regions at ply interfaces, with corresponding contributions to toughness [21].

Inclusion of particles in a matrix is reported to develop a variety of micromechanisms that may contribute to energy absorption and crack-tip shielding processes [22] including: crack deflection, crack bridging, crack-tip blunting, particle-matrix interface debonding, and particle-induced localised yielding [14, 20, 22-26]. Whilst these micromechanisms are reported, there is much debate regarding which of these micromechanisms contributes significantly to toughness. There are many factors that may be anticipated to contribute to this such as particle size, particle geometry, volume fraction, particle/matrix interfacial adhesion and particle elastic properties; making comparisons difficult between published studies [3, 14, 22, 27].

The present work compares four particle-toughened systems and one system with no particles (untoughened) to gain a phenomenological appreciation of the roles that particles may play in impact damage resistance. To complement conventional methods of instrumented impact testing and ultrasonic C-scan inspection, synchrotron radiation computed tomography (SRCT) has been used for the assessment and quantification of damage micromechanisms. The use of SRCT in composite damage analysis has been reported previously [21, 28-32]. To the authors knowledge this is the first time such high resolution CT has been used to assess the three-dimensional micromechanistic role of toughening particles during impact, with novel quantification of crack deflection and bridging processes being provided.

2 Materials and methods

2.1 Materials

Five proprietary unidirectional prepreg material systems were tested. These materials encompassed one untoughened epoxy system containing no toughening particles (UT) and four particle-toughened systems (T1-T4), labelled in order of impact damage resistance as measured by the size of the projected delamination area obtained through ultrasonic C-scan (T1 being the least damage resistant and T4 the most). For the particle-toughened systems, thermoplastic particles have been introduced to the base epoxy resin. Different particles (particle size and chemistry) were used in each of the particle-toughened systems and the same base resin was used across all five systems. Across all systems, the same fibre to matrix ratio by weight was used, and for the particle systems the same ratio of particles to resin by weight was used to form the matrix. The same intermediate modulus carbon fibre type was used in all five cases. The mode II fracture toughness supplied by the manufacturer was normalised by dividing the corresponding fracture toughness by the system with the largest fracture toughness. This led to normalised mode II fracture toughness values for the UT, T1, T2, T3 and T4 systems of 0.4, 0.8, 0.3, 0.6 and 1 respectively.

For each system, ASTM D7136M standard panels were manufactured, consisting of a 24 ply layup with a [45/0/-45/90]_{3S} stacking sequence. Panels were vacuum-bagged and fully cured under pressure in an autoclave oven to the manufacturer's specifications. Panel thickness was approximately 4.5 mm +/- 0.2

mm across the systems tested. Panels were cut using a water jet followed by end milling on a CNC machine to create test coupons measuring 100 x 150 mm to within the tolerances of D7136M.

2.2 Impact and ultrasonic C-scan testing

Prior to impact, coupons were ultrasonically C-scanned to check for gross manufacturing defects. For each material system, coupons were impacted at room temperature (23 °C) according to ASTM D7136M procedures at target impact energies of 25, 30, 40 and 50 J; these were repeated three times. An instrumented drop tower was used for this purpose. Actual impact energies were corrected for friction lost in the drop tower test frame: in all cases, the achieved impact energy was within 3 J of the target energy. Absorbed energy was derived from force-time, impact velocity and impact mass data. Post-impact, the dent depth of each coupon was measured using a TaiCaan-KeyenceTM non-contact surface profilometer and the projected damage area, a representation of the extent of delaminations, was measured using an NDT SystemsTM ultrasonic C-scanner.

2.3 SRCT scan procedure

SRCT experiments were performed on the TOMCAT/X02DA beamline at the Swiss Light Source (SLS), Paul Scherrer Institut, Villigen, Switzerland. SRCT was undertaken to study damage micromechanisms across all five material systems subjected to an impact of 30 J. A voxel size of 1.5 µm was used at an energy of 19 kV with a sample to detector propagation distance of 39 mm. To understand particle toughening micromechanisms and capture the region ahead of the crack tip, a ~5 x 5 mm region of interest towards the edge of the damaged region (as determined from C-scans) was cut out to form a 'cube' sample for each material system. To make use of automated sample handling facilities at TOMCAT, these 'cubes' were mounted on standard SEM stubs [33].

2.4 Quantification of damage mechanisms

Quantification of crack bridging and deflection was undertaken from SRCT data on each of the five material systems. For the purposes of this paper, the same delamination ply interface was studied across all material systems, specifically the first [-45/90] interface below mid-plane. This was chosen as damage in this region was captured across all material systems.

A schematic illustrating the quantification process of crack bridging is shown in Figure 1. A sampled region 300 px wide was selected, the location is shown in (a) parallel to the crack surface. To quantify bridging behaviour, the sampled region was orientated so slices were (b) perpendicular to the nominal crack front. Cross-sectional slices were spaced at one voxel intervals. The crack was “binarized” by simple grey-scale thresholding (c) with the threshold value being determined and checked by thorough visual inspection. Any binarized noise surrounding the crack was removed manually using a graphics tablet. A MATLABTM script was prepared to read the binarized image slices and used to determine the shortest interconnected distance between crack segments in regions of bridging, shown in (d). A series of 200 voxel (i.e. 300 μm) sub-areas from the crack tip towards the wake of the crack was used. This dimension is essentially nominal, being selected to measure the average extent of bridging as a function of increasing distance from the crack tip, with a distance of 300 μm being seen to capture at least five bridged regions within the sub-area near the crack tip in each of the material systems. The lengths of bridged regions within each sub-area were summed to give a total accumulated length of interconnectivity for that sub-area and averaged across all 300 cross-sectional slices for that sub-area position relative to the crack tip.

In addition to the extent of bridging along the crack wakes, the average number of bridging ligaments was also measured. Crack bridging was furthermore noted to occur in two distinct modes, with either overlapping or non-overlapping crack sections, see Figure 1 (e), which were identified respectively as ‘oblique’ and ‘perpendicular’. In the overlapping case, this is defined where one crack segment extends over another crack segment in the through-thickness direction and is indicated by the shaded region in (e).

Quantification of crack deflection was carried out on a 500 x 500 voxel (750 μm x 750 μm) area at the wake of the crack, approximately 2 mm from the crack tip; see Figure 2 (a). A manual process of tracing a line profile on the fracture surface of the side of the crack was undertaken using a graphics tablet. The cross-section was orientated with the side of the crack perpendicular to the normal crack front. Due to the laborious nature of this task, this was done at 25 cross-section intervals (30 μm spacing) to obtain a reasonable representation of the crack.

For each cross-section, the length of this fracture profile, Figure 2 (b), was measured and divided by the projected length to indicate the increase in path length as a ratio. This was achieved by calculating the

distances between the pixel centres representing the profile using Pythagorean Theorem. A conventional description of surface roughness was also obtained in terms of the R_a arithmetic average value:

$$R_a = \frac{1}{n} \sum_{i=1}^n |y_i| \quad (1)$$

Where n represents points along the trace of the fracture profile, y_i is the vertical distance from the mean line to the i^{th} data point. In both sets of measurements the standard error in the mean was calculated for path length and roughness measurements.

3 Results and discussion

3.1 Mechanical testing

The results of the mechanical testing are summarised in the graphs shown in Figure 3. The projected damage area obtained from ultrasonic C-scans is plotted against impact energy in (a) to give an overall representation of damage resistance for each of the materials. Damage areas were normalised by dividing values against the largest measured damage area allowing trends between the material systems to be compared. The variability of damage area between repeated tests was considered reasonable across all systems (on the order of $\pm 10\%$ in terms of total range) with the exception of T3, with best fit lines being plotted. A linear fit is not shown for toughened T3 system due to greater variability seen in damage areas in this system at the two highest impact energies (~ 40 and 50 J).

In general, a positive linear correlation between impact energy and projected damage area is observed. There is a clear distinction in impact damage resistance between the UT system and the T4 particle system for all impact energies tested. The T4 system is shown to suppress the extent of damage by approximately four times when compared to the UT system, and outperforms the other three particle systems in terms of damage area for a given impact energy. T1 and T2 materials fall between the bounds proscribed by UT and T4, with T2 showing a small but consistent improvement over T1. The cause of the scatter in the T2 and T3 systems at the higher impact energies is unknown: careful cross-checking for anomalies in the instrumented impact data and sample micro-structures revealed no simple explanation of variations between otherwise identical tests. For the purpose of this paper, impacts of 30 J are studied in

greater detail from SRCT scans: at these energies, variability between individual tests is modest (within $\pm 10\%$ of trend lines). A clear separation is seen between the untoughened and particle-toughened systems, and there is a consistent ranking of damage area resistance (low to high) $UT < T1 < T2 \approx T3 < T4$.

Comparing the impact damage resistance against mode II fracture toughness, the T4 systems with the highest fracture toughness correlated to the highest impact damage resistance. Regarding the other particle-toughened systems there is little correlation between mode II fracture toughness and the corresponding impact damage resistance performance which suggests a possible strain-rate dependency on these material systems. For example the T2 and T1 systems had the lowest and second highest mode II fracture toughness values respectively yet still resulted in similar impact damage performance. This highlights the unreliability of fracture toughness values that are determined through quasi-static tests to inform the damage resistance under dynamic impact events, even when classed as low velocity. For this reason, it is important to relate the SRCT observations and measurements on impact data, as discussed later, directly to its effect on impact damage resistance.

The energy absorbed by each of the five materials is plotted against impact energy in Figure 1 (b). For each system there is a distinct linear correlation (R^2 values in the order of ~ 0.97), of increasing absorbed energy with increasing impact energy. Variations between materials are generally modest, with the UT material exhibiting the highest absorbed impact energies, and T2 and T3 exhibiting the least.

Interestingly there is no simple mapping of the ranking of damage resistance (by C-scan measured areas) to the absorbed energies. One explanation is that C-scan typically only measures the projected delamination area however the energy absorbed can go to local deformation, matrix cracking, delaminations and fibre fracture [34]. This can be further complicated by the energy release rate [35] where more energy is required to propagate delamination and the distribution of the delaminations in the through-thickness.

Dent depth was plotted against impact energy in Figure 1c. At the energies tested, dent depth increases approximately linearly with impact energy for all systems (R^2 values ~ 0.95). At 25 J, all systems exhibit roughly the same impact dent depth of ~ 0.15 mm. At higher impact energies there is a clear divergence,

with the UT system exhibiting the largest dent depths. However again, the damage resistance of the material does not correlate simply with the extent of the dent. In this case the T4 material with the highest damage area resistant properties resulted in the second largest dent depth for a given impact energy. The lowest dent depth was observed in the T2 and T3 systems. Impacts around 25 J for the untoughened composite, and 30 J for the toughened systems, fell within the typical BVID regime (~ 0.3 mm dent depth). Interestingly the ranking of absorbed energy correlates with dent depth. The T1 and T4 systems may exhibit greater local ductility hence the larger absorbed energy and dent depth to the T2 and T3 system.

A plot of impact force against deflection is shown in Figure 1 (d) representing impact from each of the five material systems subjected to a targeted 30 J of impact. It is clear the UT material has absorbed the greatest energy, consistent with Figure 1 (b). Beyond some mild oscillations in load seen in all cases, a distinct load drop was consistently seen in the UT and T3 tests as indicated by arrows in Figure 1 (d). It has been reported previously [31, 36, 37] that the load drops arise from the effective brittleness of the material, indicating the onset of delamination and sudden loss in stiffness. Higher toughness systems generally tend not to exhibit a load drop, but exhibit non-linearity during the load increase during impact [26].

3.2 Damage micromechanisms

Cross-sectional SRCT slices showing delamination near the crack tip of each of the material systems are presented in Figure 4. A typical delamination crack is shown occurring in the interlaminar regions between two ply interfaces as illustrated in (i). In contrast to UT, the delaminations in the T2 system (ii) are observed to propagate within the intralaminar region, typically several fibre diameters into the corresponding ply. This mechanism was confirmed via cross-sectional optical microscopy on another test coupon to check for conformity of this feature.

A key microstructural difference between the UT system and the four particle-toughened systems is clearly the presence of an approximately ~ 20 μm thick resin-rich region, as highlighted in Figure 4 (iii), attributable to toughening particles occupying space within this region [38]. The thickness of the resin-rich region is consistent across all four particle toughened systems studied despite a difference in particle sizes used for the study. This is largely attributed to the consistent particle-resin concentration by weight

between systems, *i.e.* smaller particle sizes enabled more particles to be used resulting in a similar volume of particles occupying the resin-rich region.

The resin-rich region appears to play a direct role in toughening in the T1, T3 and T4 systems, with failure occurring both within and at the interface of these regions. The echelon crack segments indicate that failure occurred predominantly in shear in agreement with previous studies [38, 39]. Such behaviour supports the phenomenon that delamination propagation caused by low velocity impact occurs predominantly in mode II [37, 40-43]. In the case of the T1 and T4 systems where the particles can be directly observed in the SRCT images, deflections of cracks are observed around the particles, this is shown in Figure 4 (v). Such deflection can be seen to increase the crack path length, and hence the potential to increase energy absorption. Additionally, crack bridging is observed, creating traction sites between the upper and lower crack faces. Whilst toughening particles in the T3 material system could not be visualised directly, the crack morphology is comparable to both the T1 and T4 systems, with the extent and frequency of crack deflection lying between these two systems.

In the T4 system, smaller particles enabled two to three particles to fill the thickness of the resin-rich region instead of single large particles as seen in the T1 system. In some instances this appears to have allowed crack bifurcation as highlighted in Figure 4 (iv) within the thickness of the interlaminar region, increasing the fracture surface area within a shorter crack length. However, the frequency of such multiple crack formation instances was low - accounting for less than 1% of the total damage area investigated, and therefore may be considered a relatively minor micromechanical effect.

An in-plane cross-sectional slice of delamination micromechanisms in the T1 system is shown in Figure 5; the box in (a) highlights the location of the magnified image in (b) which is ahead of the main delamination crack tip. A 3D segmentation of this region in (c) shows the crack morphology within this region with cracks represented in red and particles in grey. Particle-resin debonding is highlighted at points (i) and (ii), with similar processes also being observed in the T4 system. Such particle-resin debonding may be seen as an energy absorption process itself occurring well ahead of the main continuous crack, although the energy absorption relative to that of neat resin failure is not strictly known. Such discontinuous failure also leads to bridging ligaments in the crack wake. It is very apparent from the 3D SRCT imaging that the distinction between such processes occurring ahead of, or in the wake of such

ligamented and deflected cracks is difficult to distinguish and may be best considered overall as a continuous semi-cohesive zone. Observations of delamination cracks along the fibre/matrix interface at points (iii) and (iv) show crack propagation parallel to the fibre directions at these boundaries, most likely consisting of fibre-resin debonding. This effect accounted for approximately 4% of the total delamination area in the T1 system, and is also observed in the wake of the crack circled in Figure 6 (i).

In terms of the potential toughening mechanisms described above for particle containing materials, the behaviour of the UT system reveals clear differences: in Figure 4 the absence of particles and a thick resin-rich region evidently confines delamination cracking to a narrower interface layer; with little or no crack deflection and bridging. Whilst there is some ligamented behaviour in the crack wake, these ligaments have cross-sections of the order of a single fibre spacing, *i.e.* considerably smaller than those observed in the T1, T3 and T4 systems.

As shown in Figure 4 (ii), delamination in the T2 system takes a different path and has a different morphology compared to the other particle systems. Despite the presence of a similar resin-rich interface region, the great majority of delaminations observed in this material deflected out of the resin-rich region and propagated within the adjacent ply, parallel to the ply interface. It is possible that the local toughness of the interface and matrix is high enough to prevent damage formation from occurring in the interlaminar region. This may be cause for the crack path to propagate into the intralaminar region following a path of lower resistance. The deflection of delaminations into the intralaminar region results in the potential reduction of energy absorption and crack tip shielding processes experienced in the interlaminar region as observed in the other particle-toughened systems. This potentially contributed towards the lowest mode II fracture toughness in comparison to the other systems and has a direct effect on its ability to suppress the extent of damage area as evidenced by a lower damage resistance compared to the T4 system.

3.3 Quantification of crack path length, roughness and crack bridging

Several toughening parameters were measured from SRCT data: crack path extension, roughness, and bridging behaviour. Measurement of these parameters would indicate if there is any significant contribution from these toughening mechanisms and how they compare between material systems of varying impact damage resistance.

Measurements of crack path length and roughness were taken from regions within the wake of the crack shown in Figure 6 and plotted in Figure 7. A plot of actual-to-projected crack length ratio for each of the material systems tested is shown in (a) and roughness in (b). The measurement of these two parameters is indicative of an increase in fracture surface area, and crack deflection. It is generally agreed that an increase in crack path length would absorb more energy through increased fracture surface area i.e. more energy is required to propagate the crack [3]. Toughening through crack deflection is obtained by deflecting the crack so its orientation is away from the path of maximum global strain energy release rate.

Across all the systems, there is an increase in crack path length due to some degree of crack deflection. The increase in crack path length was lowest in the UT and T2 systems, presumably due to the constraint imposed on the crack path by the relatively thin interlaminar (UT) and intralaminar (T2) resin regions. In the T1, T3, and T4 systems, a greater extent of crack deflection is evidenced by a consistent but modest increase in crack path length, actual-to-projected length ratio (from ~1.2 to 1.4). This has led to an increase in fracture surface area (~17%) in the toughest T4 system therefore increasing the energy absorption in generating the projected crack area. This is a small but important contribution to toughness, however in this case the marginal increase in crack path length is unlikely to have a significant contribution to the overall impact damage resistance, in similar agreement with another study [3].

The measurements of crack wake roughness in terms of R_a are broadly consistent with the qualitative observations of crack deflection and crack length measurements: the particle-toughened systems show greater crack roughness in the crack wake compared to the untoughened and T2 systems, as shown in Figure 7 (b). Toughness does not scale simply with surface roughness however, with the T4 system exhibiting the greatest toughness but only an intermediate R_a value. The high surface roughness observed in the T1 system is due to the larger particles used in this system and these lead to large deflected crack segments, relative to the other systems. In comparison, the T4 system, in spite of approximately 30% less roughness, an indicator of shorter crack deflections, showed approximately 120% more deflected segments, resulting in a larger crack path extension. It is difficult to say if crack deflection contributed significantly to toughness, by reorienting the crack to a plane of lower stress. It is also possible that a contribution to the toughness resulted from the deflective nature of the crack forming bridging sites, which is a separate toughening mechanism discussed next.

Extents of crack wake bridging and the number of crack segments are plotted in Figure 8 and Figure 9 respectively. The extent of interconnectivity shown in Figure 8 (a) is greater near the crack tip in the particle systems; approximately 70-100% more compared to the untoughened system. With the exception of the T2 system, it is evident that the extent of bridging drops as a function of distance from the crack tip. This decrease may be simply associated with increasing ligament strain, and hence propensity to fracture, as crack opening displacements increase with increasing distance from the crack tip. The T3 and T4 systems have a ~30% smaller average ligament size near the crack tip compared to T1 and T2, see Figure 8 (b), however there is approximately 100% more ligaments, as shown in Figure 9 (a) and (b) - this has led to a larger accumulated extent of bridging.

Two categories representing the number of bridging sites as a function of sub-area distance from the crack tip are shown in Figure 9 consisting of oblique and perpendicular cracks. The proportion of oblique ligaments is generally much lower than the perpendicular ligaments, with the exception of the large particle containing T1 system, where a consistently greater proportion of oblique ligaments are seen. In relation to damage resistance, it is clear that the more resistant materials (T2-T4) are dominated by perpendicular ligament formation, particularly in the near-tip region.

With the exception of T2, the average size of the ligaments decreases away from the crack tip. This is due to the growth of crack segments reducing the size of the bridging ligaments; see Figure 8 (b). The scattered nature of bridging in the T2 system in the crack wake circled in (b) is due to the crack deflecting from the intralaminar region into the resin-rich region, see (i) in Figure 10. The T3 and T4 systems have a larger number of non-overlapping crack segments which decrease in number density with distance from the crack tip. This decrease in number is attributed to crack growth and fracture of the bridging ligaments. This characteristic is observed in the UT, T1 and T2 systems beyond 1.2 mm from the crack tip.

It is clear that bridging ligaments near the crack tip, as represented by the total interconnectivity in Figure 8 (a), offers some indication to the corresponding impact damage resistance performance and can be ranked in terms of low (UT), intermediate (T1, T2 and T3) and high (T4). However, the relative improvements to the extent of interconnectivity between systems do not always correlate to the same magnitude of improvements in impact damage resistance, particularly between T3 and T4 systems. This suggests that whilst bridging ligaments may offer a significant contribution towards impact damage

resistance, it is likely to be in conjunction with other parameters not measurable through SRCT which can only capture geometrical information. A key question is how the T4 system provides superior damage resistance, quantified as a 75% reduction in damage area at a similar impact energy level compared to the untoughened system. Due to the difference in failure in the T2 system, the most direct micromechanistic comparisons may be drawn between the materials exhibiting true interlaminar failure, *i.e.* UT, T1, T3 and T4. From the quantification of increase in crack path length, roughness, and bridging behaviour, both T3 and T4 systems show comparably similar results despite a 50% lower projected damage area in the latter material system. This is interesting as one would expect to see a significant increase in the extent of one of these mechanisms. This suggests that whilst these toughening strategies are important characteristics to consider, there are other factors that need to be understood which are not measurable from this SRCT data, therefore requiring other complementary experimental techniques. These include, but are not limited to the inelastic deformation in the bridging ligaments, the resulting bridging traction-deflection behaviour, the stiffness of particles bridging the delamination to reduce crack tip stresses and energy absorbed by particle-resin interfacial debonding and other factors such as fibre fracture.

4 Conclusions

As evident from mechanical testing and ultrasonic C-scans, particle-toughened systems show an improvement in low velocity impact damage resistance compared to the untoughened system. In this study, the T1, T2 and T3 systems improved damage resistance by a factor of two, and the T4 system by a factor of four when compared to the untoughened (UT) system at a 30 J impact. A poor correlation between mode II fracture toughness and corresponding impact damage resistance was observed across the material systems studied suggesting strain-rate dependency on some systems. For this reason, characterisation of toughness observations and measurements from SRCT impact data were compared directly to the impact damage resistance performance.

SRCT revealed that the toughening behaviour in the T1, T3 and T4 systems consisted of particle-resin debonding, crack bridging and crack deflection. In the T2 system delaminations were driven into the intralaminar region.

Quantification of the increase in crack path length, roughness and bridging behaviour was undertaken via SRCT-derived images. A small ~17% increase in crack path length was observed in the most damage resistant system. It is considered that the contribution of an increase in crack path length as a toughening mechanism is small in comparison to the extent of bridging where a significant increase in this mechanism was observed in particle toughened systems which correlated with gains in impact damage resistance. Whilst this study quantified these behaviours, it was unable to correlate this to the superior damage resistance in the T4 system, suggesting that additional factors need to be considered and further complementary work is required.

The measurements provided in this paper indicate the potential of high resolution computed tomography to quantify the relative effects of toughening mechanisms in structural materials. The ability to quantify these mechanisms is an important element in the independent calibration of micro-mechanical models for fracture and failure processes. This represents an opportunity to pursue a strategy of data-rich mechanics, whereby limited numbers of *in situ* experiments can yield sufficient data to allow for the validation and calibration of sophisticated damage-based micromechanics models.

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Figure 1 – Crack bridging measurement process. (a) Schematic showing the location of the sampled region within a segment of delamination. (b) SRCT cross-section of the side of a delamination. (c) Binarization of the crack with the crack profile divided into 200 px sub-areas. (d) Close up of a sub-area with shortest distances between crack segments measured. (e) Example of overlapping (oblique) and non-overlapping (perpendicular) crack segments..

Figure 2 – SRCT cross-section of delamination in the wake of the crack. (a) overlay of the lower fracture profile, (b) segmentation of the fracture profile where the length of the profile is divided by the projected length to calculate the increase in crack path length as a ratio.

Figure 3 – Mechanical testing plots: (a) Normalised projected damage area vs. impact energy, (b) energy absorbed vs. impact energy, (c) dent depth vs. impact energy, and (d) impact force vs. deflection.

Figure 4 – SRCT cross-section of delamination formation towards the edge of the damaged region. (i) delamination within the interlaminar region, (ii) delamination/longitudinal ply split within the intralaminar region, (iii) resin-rich region, (iv) multiple crack formation, (v) close up of overlapping crack deflection in the T1 region indicated by the box.

Figure 5 – T1 SRCT volume showing (a) cross-sectional slice of delamination at the resin-rich region, the box indicates a close up location shown in (b) with (c) showing a 3D segmentation of cracks in red, and particles in grey. (i) and (ii) indicates particle-matrix debonding, (iii) and (iv) highlight delamination cracks propagating along the fibre-resin interface.

Figure 6 - SRCT segmentation of delamination areas taken in the wake of the crack at the same ply interface position for the five material systems. (i) Delamination cracks propagating along the fibre-resin interface.

Figure 7 – (a) Ratio of actual-to-projected crack length for each of the material systems tested. (b) Fracture surface roughness across the five material systems.

Figure 8 – Plot of bridging behaviour as a function of sub-area distance from the crack tip. (a) The total interconnectivity in each sub-area, and (b) the average ligament size in each sub-area. The circled region in the T2 system represents the crack deflecting back into the resin-rich region.

Figure 9 – Plot showing average number of bridging sites in sub-area for overlapping and non-overlapping crack segments.

Figure 10 – Cross-section of T2 system. (i) Crack deflected into resin-rich region at 900-1500 μm from crack tip.