Damage progression in Tow Based Discontinuous Composites under static indentation testing.

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1. Abstract

Static indentation testing was carried out on Tow-Based Discontinuous Composites (TBDC) with a range of tow lengths and a continuous Quasi-Isotropic baseline (QI). All TBDCs were found to withstand lower indentation forces than the QI, and had a lower total energy for a given indentation depth. Longer tows did withstand higher indentation loads and had greater indentation energies for the same depth compared to shorter tows. However, delaminated areas for shorter tow lengths were significantly smaller than for long tow lengths and QI material. Future work will continue indentation tests and carry out interrupted testing to analyse the initiation and progression of damage in greater detail.

2. Introduction

Despite the fibre reinforced composites allowing sizeable mass and fuel savings through improvements in specific strength, there are significant underlying problems relating to sustainability. One of the key challenges is the potential for poor residual strength under impact loading [1]. This is exacerbated by the accumulation of interlaminar fractures during repeated Barely Visible Impact Damage (BVID), which can lead to serious reduction in critical component strength [2,3]. These lead to increases in component mass to offset any in service damage that may occur. Furthermore, the premature retirement of components and inspections are expensive, but also they contribute to the ever growing challenge of composite waste. The composite industry recycles less than 90% of waste [4], in addition, disposable restrictions are becoming increasingly stringent [5], creating a multifaceted problem the composite industry must solve.

Significant developments to improve the impact performance of composites have been undertaken; these fall into the main categories of energy dissipative mechanisms or structural reinforcement [6]. The spread of delamination has been shown to be limited by means of through thickness reinforcement [7,8], whilst plastic deformation has been exploited to dissipated energy by applying thermoplastic matrices. Matrix modifications can also be applied, either to absorb energy through ductile failure or to create localised bridging and crack deflections [9]. These inclusions greatly increase the crack face roughness and thus surface area, increasing the energy dissipated over a given area. Similar complex crack paths have been seen in TBDC laminates under impact, but few studies have been conducted in this field[10].

Discontinuous composites have long been a mainstay of the composite industry. Chopped strand spray moulding and injection moulding of fibre reinforced thermoplastics are commonly applied in industries requiring low-cost parts with complex geometries [11,12]. Until recently, the key benefits have been low-cost feedstock materials, however increasing attention is being directed towards the application of recycled fibres. However, their mechanical properties are limited. More recently, greater interest has been applied to Tow Based Discontinuous Composites (TBDCs). The tow based mesostructure allows greater fibre volume fraction (Vf) and a multi length scale or hierarchical failure regime as inter and intra tow failure is present [13,14]. This hierarchical failure system has demonstrated significant notch insensitivity, with localised delamination and crack fronts creating pseudo-plasticity within the composite [15]. As the damage spreads, crack fronts are diverted and blunted by the random orientation of the chopped tow, whilst stress redistribution occurs around the damaged area. All this culminates in a material able to effectively absorb energy, which if applied to impact could allow for more damage tolerant structures.

Impact damage studies for TBDCs are sparse, with previous works analysing discrete energy absorption or the residual strength through compression after impact testing. Impact testing demonstrated an increase in energy absorbed and lower peak force compared to continuous QI composites [10]. Impact sites demonstrated complex geometries dissipating energy over a large surface area for a given volume. Moreover, a reduction in compression strength is found, however this is offset by a much lower initial strength. No studies have looked at the initiation and progression of impact damage over a large range of energies. Such studies have been applied for continuous QI composites utilising static indentation testing [16]. Instead of low velocity drop testing, where an impact energy is applied and indentation, and energy absorbed are recorded, an indenter is depressed into the laminate with force and displacements recorded. This allows greater control over the test end point and the possibility of interrupted testing, allowing greater precision in tracking the onset and progression of impact damage.

This study has applied static indentation on TBDCs on fibre lengths ranging from 6 to 48 mm to analyse the progression of impact damage and assess the effect of fibre length on the impact properties of TBDCs.

3. Materials and Methods

Standard modulus Carbon Fibre (CF) tow was chopped to nominal lengths of 6, 12, 24 and 48 mm. It must be noted, some slippage of the feed roller did occur therefore a variation of fibre lengths were present, the 12 mm tow batch was most effected with lengths between 9-12 mm present. The tow weight was 800 tex with an approximate area weight of 133 gsm. Non-Crimp Fabric (NCF) was used to create a baseline QI laminate. Cross-ply (0, 90) and biaxial (+45, -45) plies were used to create the QI laminate, each fabric had an area weight of 388 gsm, with a ply weight of 194 gsm.

An epoxy-based binder powder was used to join the chopped tows together to manufacture the preforms. The binder powder used was soluble in excess of 110°C therefore has been assumed to not affect the mechanical properties. A concentration of 5% binder per fibre weight was used.

The resin system used was an untoughened, two component aerospace infusion epoxy system. This was used for several reasons, first the low viscosity during infusion to allow higher Vf, but more importantly the lack of matrix toughening allowed the discontinuous reinforcement to be studied with greater clarity.

3.1 Sample manufacture

Chopped tow and binder powder were combined and mixed by tumbling the mixture in a sealed container in the attempt to reduce damage to the tows. Release film and a template was laid over a tool plate, with an area of 1.05 m x 0.45 m prescribed by the template. (Figure 1a). The mixture was subsequently weighed out to cover the area at a reinforcement density of 388 gsm. The mixture was distributed over the tool plate using a soil grading sieve to create a uniform fibre bed. A sheet of infusion peel-ply was used as the top release film as this also allow air evacuation across the fibre bed (Figure 1b). A reusable silicone vacuum bag was laid over the bed and vacuum drawn. after it was placed in an oven at 120°C for 20 mins to consolidate the fibre bed into a handleable preform (Figure 1c).

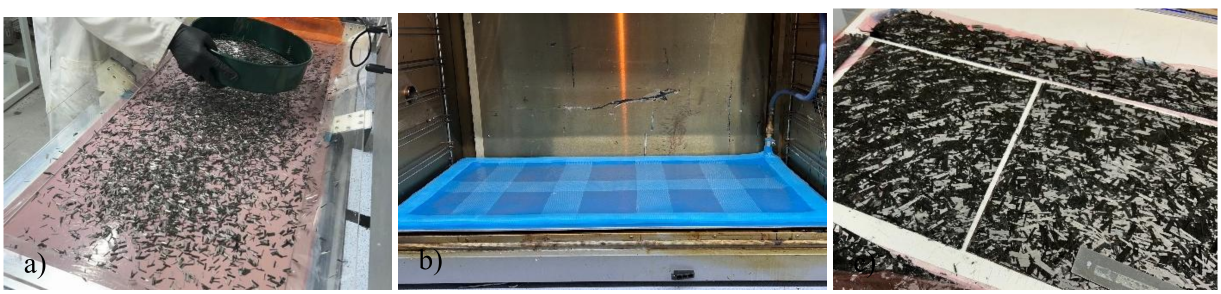


Figure 1: The process of manufacturing the dry fibre preforms, from distribution (a), to compactiona and consolidation (b) to result in a handelable, processable discontinuous material (c).

10 plies of discontinuous preform was stacked within a steel Resin Transfer Moulding (RTM) mould and closed using a hydraulic press (Figure 2). A compression RTM process was used to achieve high Vfs whilst preventing over compaction of the fibre bed and preventing evacuation of volatile vapours or creating dry spots. A reduced compaction pressure was initially applied (~0.3MPa) during drying of the fibre bed and infusion. Once infusion was complete, the pressure was ramped up (~2.5MPa) to reduce the infused laminate to final thickness. A target Vf of 52% however Vfs ranged from 48 to 55%.

The Baseline QI laminates comprised of a 24-ply symmetric, balanced laminate $[45,-45,0,90]_{S3}$ with a final thickness of approximately 4.2 mm and a Vf of 62%.

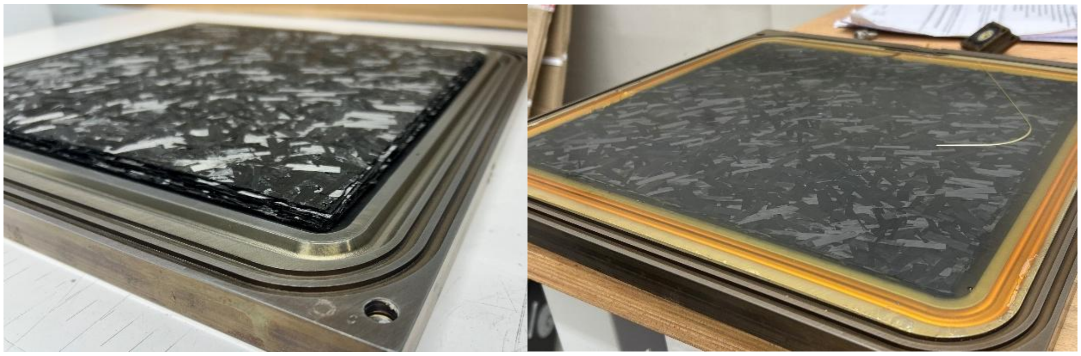


Figure 2: Discontinuous preforms stacked prior to infusion (left) with the resultant laminate after infusion (right)

3.2 Testing

Specimens were cut using a Compcut 200 composite plate saw with a diamond circular saw blade, each specimen was 60 mm x 60 mm. The specimens were clamped between two plates with a Ø50 mm diameter unsupported area for indentation (Figure 3). A clamping force of 20 kN was used to prevent delamination progressing beyond the Ø50 mm unsupported area.

A Ø16 mm indenter was depressed at a rate of 0.5 mm/min until the set depth, and then retracted at the same rate. Force and displacement were recorded for both indentation and retraction.

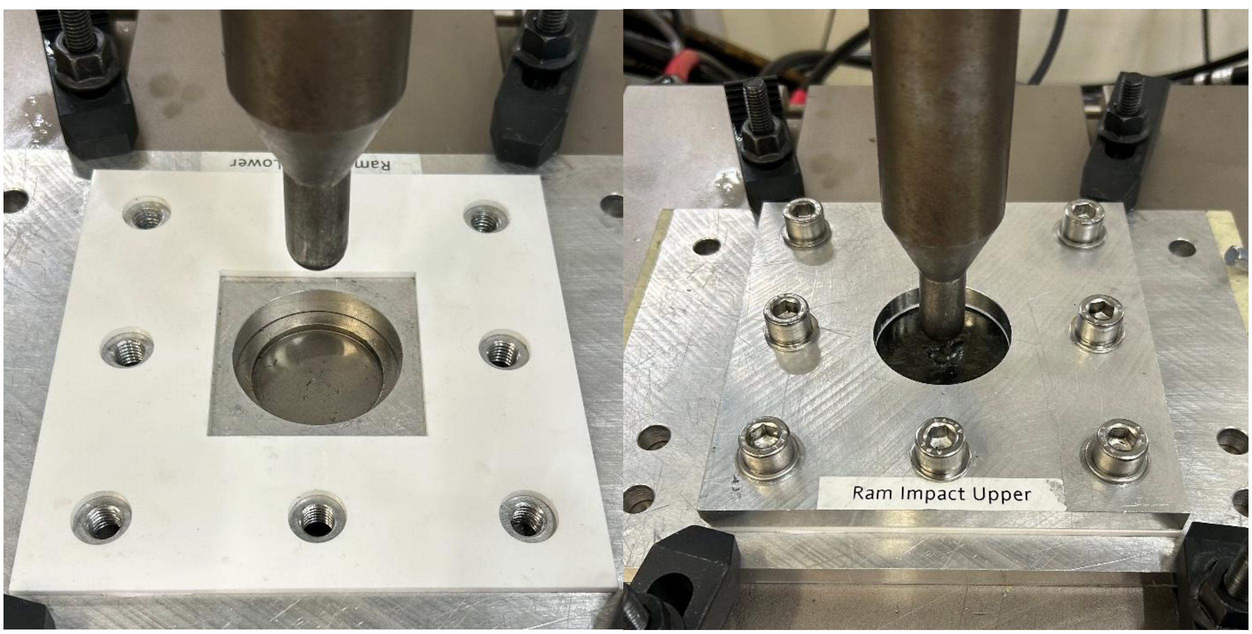


Figure 3: Static indentation apparatus used, with Ø50 mm unsupported region seen (right) and then the specimen clamped with 8 bolts to achieve uniform clamping pressure.

The recorded force and displacements were analysed and compared between each samples type. The total energy was calculated through integrating the indentation force with respect to displacement up to the max displacement, with absorbed energy estimated by subtracting the integral of the retraction data. Permanent indentation depth was recorded as the displacement the retraction force reached below 1% of the initial load.

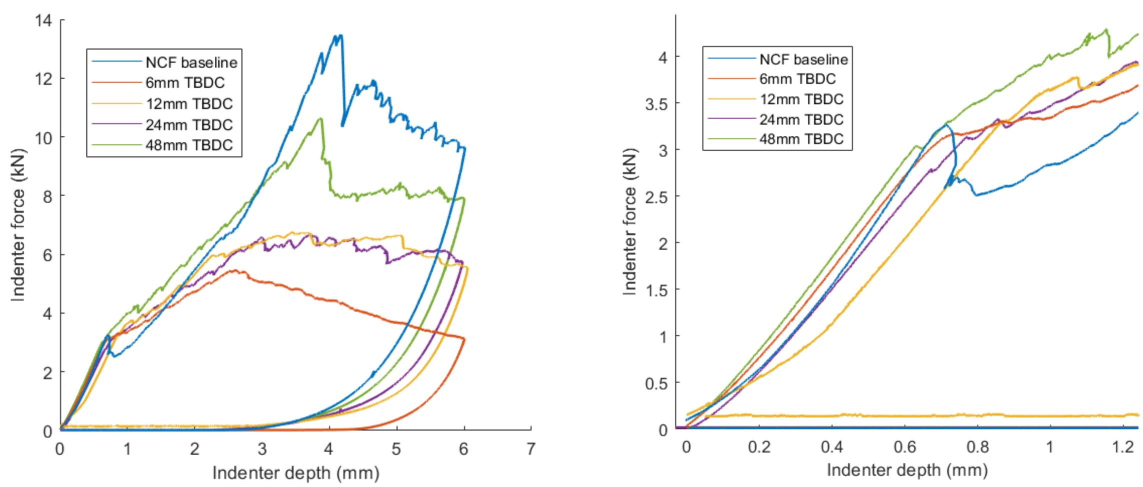
Projected delamination was measured using ultrasonic C-scan. A range of frequencies was trialled with internal reflection due to the discontinuous structure creating significant noise. The chosen probe was a 5 MHz with 76.2 mm focal length. A raster scan with a sampling step of 0.2 mm was applied and resultant C-scans analysed.

Internal damage was visualised using XCT, at a resolution of 17µm/voxel. XCT images were acquired on a Nikon XTH 225ST; 3141 projections were taken at 80kV and 139µA.

4. Results and Discussion

A comparison of the force vs displacement plots of each tow length and the baseline NCF can be found in Figure 4. The QI NCF had higher peak force than all TBDCs however, the onset of failure imitated at lower loads and displacements than all TBDCs (Figure 4b).

Within the TBDC laminates, the 48 mm tow had the highest peak force, similar to that of the NCF. But, as the tow length decreased, the peak force also decreased however all had similar loads at the end of the elastic regime. The shorter tow lengths had more gradual failure progressions beyond the ultimate load, with either a slow decrease in load or a plateau.



(a) (b)

Figure 4: Comparison of the indentation force for all material systems tested: (a) over the full 6mm indentation: and (b) the first stages damage initiation

Similar trends are present when analysing the total and absorbed energy, with shorter fibre lengths absorbing less energy for the same indentation depth at high indentation depths (Figure 6). Below indentation of 10 J however all laminates had very similar indentation energies for the same indentation depths.

When analysing the C-scans and XCT, the short tow lengths exhibited significantly lower delamination than the longer tow lengths (Figure 6 and 7). All discontinuous material demonstrated complex crack formations as the random architecture caused crack fronts to be redirected. The longer tow lengths demonstrated that delamination followed the tow, leading to much wider spread of damage than for the short tows. The shorter tow specimens faced severe damage close to the indentation site however beyond the immediate vicinity, very little damage was visible. The widest crack fronts all specimens were either found on the underside of the specimen or the mid-plane.

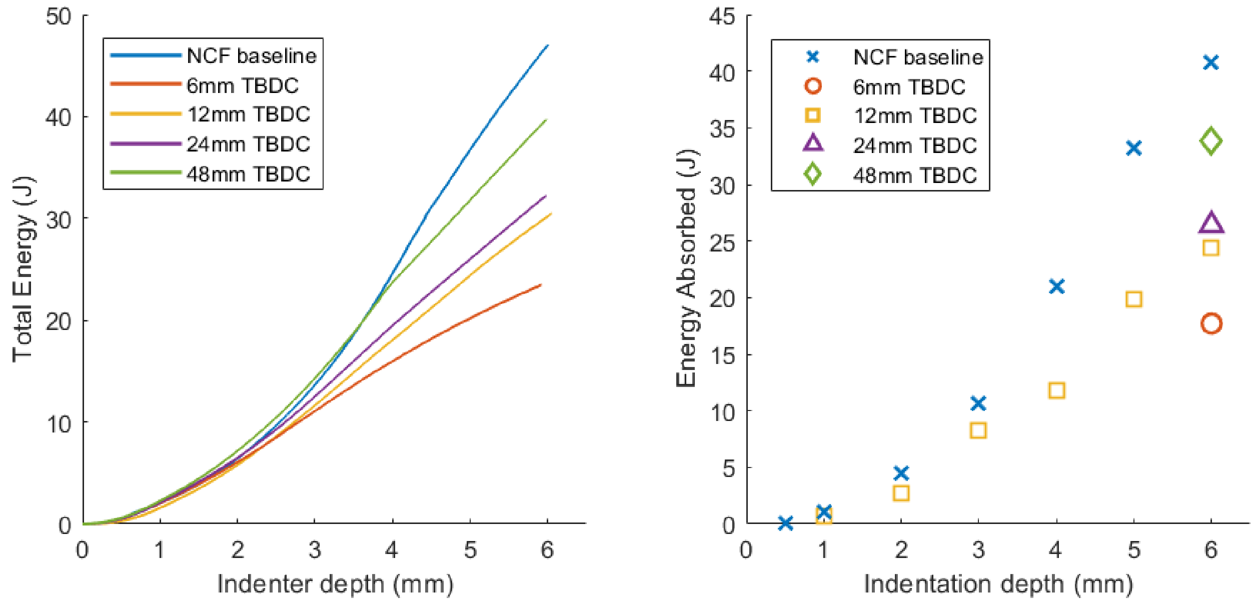


Figure 5: Total indentation energy (left) and absorbed energy (right) for all material systems.

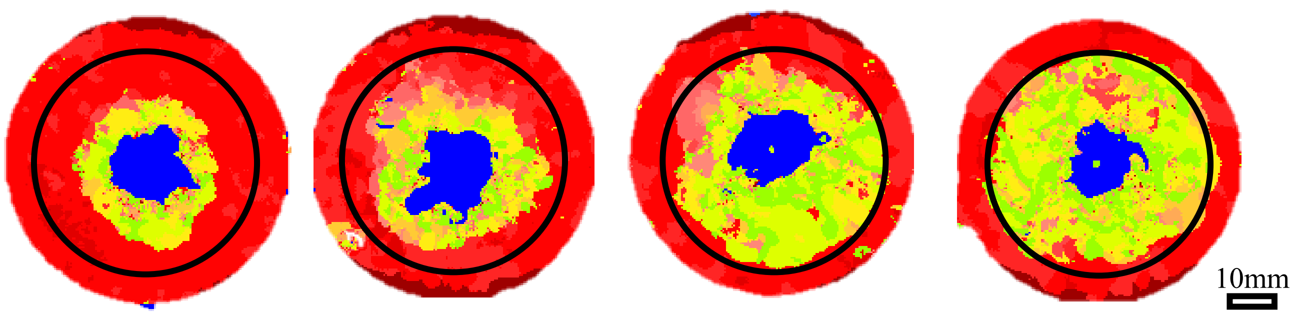


Figure 6: Ultrasonic C-scans for (from left to right) 6, 12, 24 and 48 mm tow specimens indented to 6mm, with delaminated area seen in yellow/green. The black circle marked in all tests corresponds to the edge of the clamped area

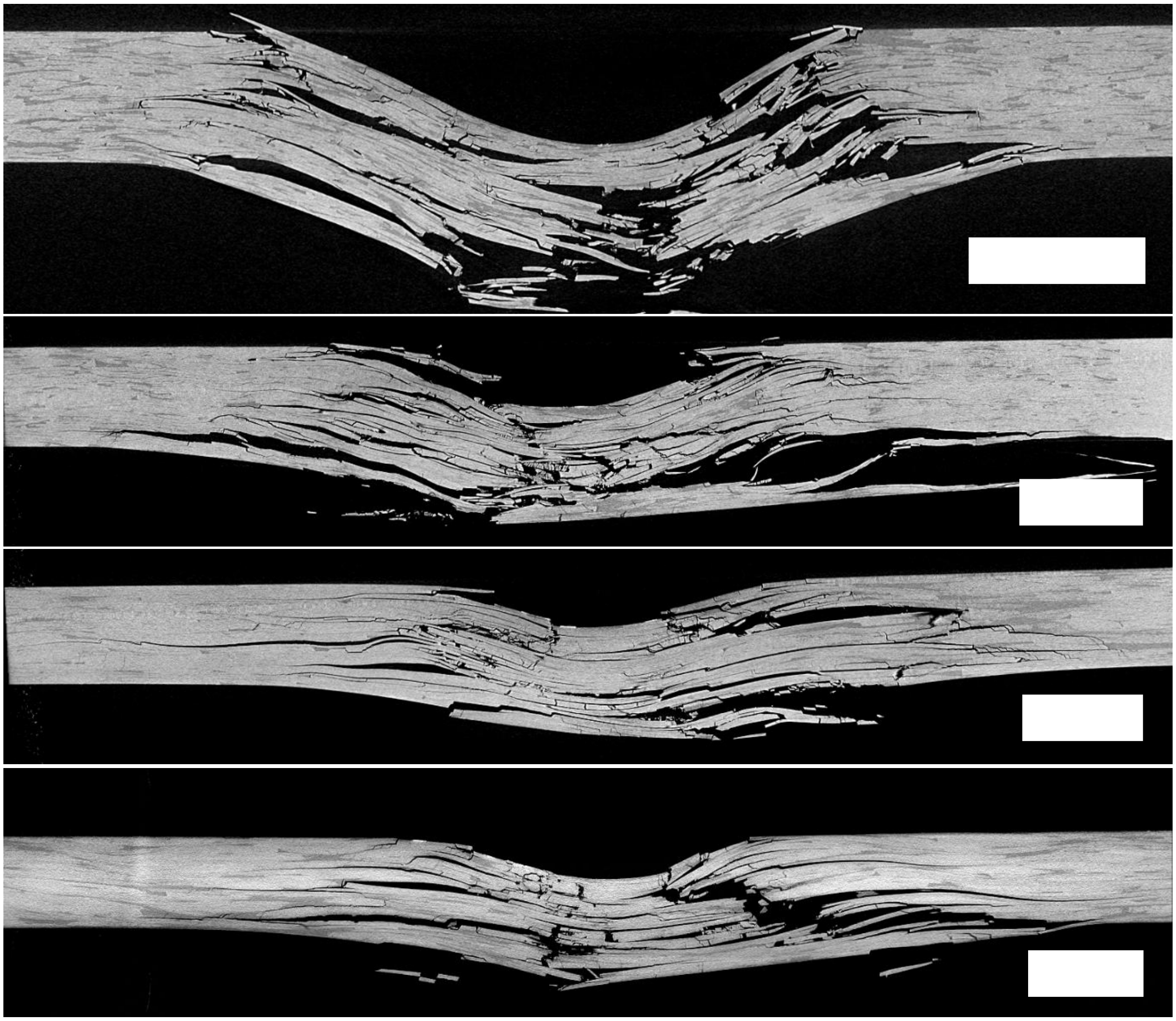


Figure 7: XCT cross sections for (top to bottom) 6, 12, 24 and 48 mm specimens indented to 6mm showing internal damage. White scale bar indicates 5 mm for all images.

The differences in ultimate load between the QI, the 48 mm tow and the short tow lengths was expected. The progression of damage as described for continuous reinforcement begins with the onset of interlaminar shear cracking, followed by the progression of delamination [16]. Once delamination has become widespread, the area around the indenter changes from being dominated by bending to greater membrane tension. Beyond this stage, failure is dominated by fibre fracture, hence the abrupt drop in load seen for the QI specimens in Figure 5a.

Standard thickness tow TBDCs have significantly reduced tensile strength and stiffness compared to continuous QI. Tensile failure for shorter tow lengths is dominated by tow pullout and matrix based damage. Furthermore, due to the shorter tow lengths, the distance over which stress is transferred by individual tows is reduced. On the other hand, TBDCs with longer tows exhibit fibre fracture as the predominant ultimate failure mechanism.

Therefore, as damage initiates and a reduction in stiffness can be seen in Figure 5b, a slower rate of stiffness reduction can be seen for shorter tow lengths, whilst a large load drop is present for the QI specimen. The slow stiffness reduction is the start of the accumulation of delamination and localised tow pullout. Whilst the longer tows demonstrate greater stiffness retention due to the higher proportion of fibre loading and greater distribution of stress across the specimen.

Beyond this point, delamination and interlaminar shear initiated matrix cracking progresses to the point of ultimate failure. However, the 6 and 12mm tows showed severe localised damage (Figure 7), whilst the 24 and 48mm had more diffuse damage affecting a greater area.

The shorter fibres and lower tensile strength prevents the spread of damage as delamination, while tow pullout only affects the material on short length scales. This is in addition to greater numbers of randomly oriented tows deflecting crack fronts. The combination of reduced stiffness combined with more severe localised damage explains that despite the lower total indentation energy, the proportion of energy absorbed is higher than that of longer tow or QI specimens.

Meanwhile, for the longer tows, as they are able to load to a greater extent, either fibre fracture occurs or more prevalently, the delamination becomes more widespread. The longer tow stays intact and the material around undergoes bending as well as membrane tension, explained by the cracking at the midplane. This combination of loading causes greater spread of delamination as the active cleaving occurring during the bending exacerbates the opening of crack fronts. This is on top of the reduced number of tows to cause redirections of the crack fronts. The combination of higher stiffness and fibre loading in turn allows a higher indentation energies, however the proportion of energy absorbed is lower, potentially improving residual strength.

5. Conclusion

Static indentation testing has been carried out on TBDC coupons with tow lengths ranging from 6-48 mm. Initial findings show longer tow lengths were able to sustain higher indentation loads due to greater fibre loading, however this was at the cost of more rapid reduction in stiffness beyond the maximum load. This is similar to the baseline NCF QI samples, where abrupt ultimate failure occurs at the onset of fibre fracture as the laminate transitions from delamination and matrix-based energy dissipation to membrane tension. Shorter tows on the other hand withstand reduced indentation loads, but the reduced tensile strength allows localised tow pull-out to occur, dissipating indentation energy effectively whilst maintaining a reduced affected area.

Further work will be focused on an interrupted testing campaign to study the progression and initiation further, aided by high resolution XCT. This will be further supported by residual strength testing.

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