1. Introduction
Understanding damage and mechanisms of failure is one of the important areas in the design and modelling of fibre reinforced composite materials. A significant amount of effort is being put into providing a thorough assessment of the availability of damage and failure criteria in conventional non-woven composite laminates made of unidirectional tape prepregs [1]. Damage and failure progression is much less well understood when dealing with the new 3D fibre reinforced composites and there is a need to understand the damage development qualitatively before confidence can be placed in quantitative modelling. The developments of novel 3D woven composite materials arise as a result of a strong need to manufacture composites that are cheap, easy to form into complex shapes, impact resistant, damage tolerant, and are sufficiently good in their other mechanical properties compared with traditional prepreg laminates [2-8]. 3D composites consist normally of tows oriented through-the-thickness as well as in the in-plane directions [9,10]. As a consequence, it is envisioned that the through-thickness reinforcement could offer substantial advantages in terms of improving the damage tolerance and lead to better lateral impact characteristics [11-14].

The aims of the current work are to study experimentally damage development in transparent glass/epoxy non-crimp 3D orthogonal woven fabric composites under tensile, flexure and quasi-static indentation tests. The mechanical behaviour of the composite specimens reinforced with a single ply 3D orthogonal E-glass woven preform manufactured by 3TEX is compared with that of a thickness- and reinforcement areal weight-equivalent 2D plain weave E-glass reinforced epoxy resin composite laminate.

2. Experimental details
2.1 Materials
Two material types were selected for the present tests and these are (a) 3-ply 2D weave and (b) non-crimp single ply 3D orthogonal weave epoxy matrix composites. Both of the fabrics were woven by 3TEX Inc, USA. The 2D fabric has an areal weight 815g/m² (24 oz/yd²). The 3D fabric has an areal density of 2640g/m² (78 oz/yd²). The resin used was a Shell Epikote 828 (Bisphenol-A) epoxy resin with a Shell epicure nadic methyl anhydride (NMA) curing agent and Ancamine K61B accelerator. The epoxy, hardener and curing agent were mixed in the ratio of 25:15:1 by weight.

The architecture of the two materials is described in detail in [15,16]. The 3D preform consisted of three layers of weft (a.k.a. fill) rovings, and two layers of warp rovings interlaced by z-roving. All of the rovings in the 2D and 3D preforms were made from PPG Hybon 2022 E-glass fibres.

The number of layers in the 2D specimens was selected so that the 2D and 3D specimens have as close as possible amount of fibres by areal weight. Three plies of dry 2D woven fabric result in 72 oz/yd² total areal weight; the respective composite is labelled “2D-72”. A single ply 3D fabric composite is labelled “3D-78” accordingly. The difference in total areal weight of reinforcement is 8%, which is a close equivalency. It also has to be noticed that 2D-72 composite specimens were 25% thinner than the 3D-78 specimens.
2.2. Specimen and testing procedure
The tensile tests were conducted using an Instron 6025-5500R servo-hydraulic testing system with a 100 kN load cell. The coupon specimens were 200 x 20 mm and the thickness was around 1.65 mm for the 2D material, and 2.19 mm for the 3D material. For the flexural tests, coupons with the same dimensions were loaded in four-point bending (quarter-point loading) with the distance between the outer rollers being 80 mm. Strain gauges were bonded at the centre of the coupons to measure the longitudinal strains on the compressive and tensile faces of the specimens.

The quasi-static indentation tests were conducted on an Instron 1341 servo-hydraulic testing system with a 50 kN load cell. The impactor was a spherical glass ball with a diameter of 16 mm, mounted on a rod that was controlled by the servo-hydraulic testing machine. The specimen tested area had a diameter of 100 mm from the initial 140 mm (further details can be found in [12]).

3. Results and discussion
3.1 Uniaxial tensile tests
Uniaxial tests were carried out in the weft and warp directions to determine the mechanical properties (strength, modulus, failure strains). The specimens showed mechanical properties that were very similar to the results published on similar 2D woven laminate and 3D woven E-glass reinforced composites manufactured with a room temperature cure Derakane 8084 epoxy/vinylester resin (those materials were manufactured using the VARTM technique, see details in [15,16]).

Crack density measurements were taken during the loading of some specimens, since the transparency of the specimens allowed crack development to be monitored using a still camera with backlighting of the specimen. A simple measurement of the plan-view crack density was used here, which summed the crack length in an area defined by the specimen width and along a prescribed length of the coupon (96 mm).

The results of crack density variation with strain in the 3D-78 composites (see Fig. 1) showed that crack initiation occurred at about the same strain level (0.7%) for both the warp and fill specimens, although the saturation crack densities differed slightly (about 0.6 mm\(^{-1}\) and 0.7 mm\(^{-1}\), respectively - i.e. a slightly higher crack density in the weft coupons).

Various crack types were detected in the specimens (Fig. 2): “straight cracks” that ran fully or partially across the width of the coupon; and “wavier cracks”, which sometimes look like two, or three, cracks close together. Indeed, as edge sectioning and microscopy have shown, the apparently wavy nature of some of the cracks is because cracks can grow in different through-thickness layers of the specimen at roughly the same location.

3.2 Flexural testing (four-point bending)
In the four-point bend tests, matrix cracking damage developed, not surprisingly, in the half of the specimen subjected to the tensile strain (note that the coupons were not taken to failure). Figures 3a and 3b show crack density/surface strain measurements for warp direction and fill direction coupons, respectively.

Warp direction coupons showed a more rapid increase in the matrix crack density with strain initially which is related to the 3D architecture. The surface of a warp-directional coupon consists of bundles of fibres (fill tows) running on the surface transverse to the longitudinal tensile strains on the surface; the consequence is that there are many sites for crack initiation. On the other hand, fill direction coupons have surfaces dominated by the fill tows running parallel to the longitudinal surface tensile strains, thus providing many fewer sites for crack initiation. Indeed, initial cracking takes place within the resin-rich regions between the warp tows which are a consequence of the path of the z-tows through the structure (Fig. 4).

3.3 Quasi-static indentation tests
In general, the force-displacement curves for the quasi-static indentation tests differed for the 3D-78 and the 2D-72 materials in that for the latter case the force against displacement curves were smoother. In both cases, the thin composite disks behave in a non-linear elastic manner on loading, in accordance with the behaviour of circular thin plates under a central point load. However, the load-displacement curves of the 3D-78 composite tend to show much larger load fluctuations as the indenter penetrates the panel (Fig. 5) which is believed to be a consequence of the loading and subsequent fracturing of the z-tows.
The prediction of the level of energy absorption under quasi-static indentation is difficult due to the variety of failure mechanisms, geometry variation, material lay-up, thickness, fibre volume fraction, indenter dimensions and materials. Caprino and Lopresto [11] showed that the penetration energies for a wide range of glass and carbon fibre reinforced materials are well represented by a simple empirical expression:

\[ U_p = 0.49 \cdot \left( t \cdot V_f \cdot D_i \right)^m \]  

Equation 1

Here \( U_p \) is the penetration energy, \( t \) is the thickness of the laminate, \( V_f \) is the fibre volume fraction, \( D_i \) is the diameter of the spherical impactor (16 mm in the present work), \( m \) is an empirical constant, taken normally as 1.4. Figure 6 shows the experimental data for the 2D-72 and 3D-78 composites together with the prediction provided by the above equation (with \( m = 1.4 \)). Although the experimental results are clustered over a small range of \( t \cdot V_f \cdot D_i \) (between 14 to 16 mm\(^2\)), the empirical equation seems to fit the data for the 2D-72 woven composite tested here reasonably well. However, Equation 1 underestimates the penetration energy by about 10% for the 3D-78 composite.

The damage development in the early stages of the quasi-static indentation test is consistent with the results from the flexure tests. Cracking initiates first parallel to the fill tows, which is in agreement with the flexure results showing the early development of matrix cracking in the warp-directional coupons. Figure 7 shows a view of the specimen from the exit face with significant matrix cracking visible in a direction transverse to the warp direction (i.e. in the fill direction).

4. Concluding remarks

1) Coupons with a high degree of transparency have been manufactured in order to be able to monitor damage accumulation during tensile, flexural and quasi-static indentation loading. The basic mechanical properties of the coupons were in good agreement with the previously published work of other authors.

2) Uniaxial tensile tests showed that matrix crack initiation in warp and weft direction coupons had occurred at a strain of about 0.7%. The crack morphology is complex, with the apparent waviness of some cracks being due to the formation of cracks in different layers of the structure. In flexural loading, warp direction coupons showed a more rapid increase in cracking due to the development of cracks adjacent to the tensile face of the coupon, either through the matrix, or through the transverse fill tows at the surface. By contrast, cracking was delayed in fill coupons and developed first in the resin pockets between the warp tows which are a consequence of the through-thickness z-tow reinforcement.

3) The quasi-static indentation tests showed that energy absorption for penetration of the 3D-78 specimens was significantly greater than that for the 2D-72 specimens. Fluctuations in the force-displacement curve are believed to be a consequence of the loading and subsequent fracture of the through-thickness reinforcement. Early damage development in these tests was consistent with the flexure results which indicated that matrix cracking damage developed initially parallel to the fill tows.

![Fig. 1. Increase in crack density with strain for (a) warp, and (b) fill direction 3D-78 coupons.](image-url)
Fig. 2. A 3D-78 composite (warp direction specimen) after an applied tensile strain of about 1.5%. The coupon is 20 mm wide.

Fig. 3. Crack density as a function of nominal surface strain (tensile face) for flexural loading of (a) warp, and (b) fill direction of 3D-78 coupons.

Fig. 4. Edge sections of flexure specimens of 3D-78 composites showing matrix cracking: (a) warp-direction coupon with surface cracking parallel to the fill tows; (b) fill-direction coupon with cracking in resin-rich regions. Coupon thicknesses are each about 2.2 mm.

Fig. 5. Load-displacement response for the quasi-static indentation of a 3D-78 specimen showing a fluctuating load response.

Fig. 6. Comparison between penetration energies of 2D-72 and 3D-78 specimens in single and multiple quasi-static indentation tests with the predictions of the empirical model of Caprino and Lopresto [11].
Fig. 7. Quasi-static indentation of a 3D-78 specimen, viewed from the exit face, for a displacement of 7 mm (point “e” in Fig. 5). Matrix cracking parallel to the fill tows can be seen (the arrow indicates the warp direction).

References


