BENDING CHARACTERISTICS OF 3D WOVEN CARBON COMPOSITES

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Abstract
This study investigates the elastic behaviour and failure modes of 3D orthogonal woven carbon composites via cantilever structural testing. Two reinforcements with varied through-thickness binder density are tested and compared. The results show no influence of binder density with long beam tests, while there are distinctive differences in post peak –load energy absorption with short beam tests.

1 Introduction

Delamination is of great concern of composite structures under bending. It has been shown that 3D weaving can provide higher delamination resistance [1]. The literature has covered extensively the in-plane performance of 3D woven composites, however, the bending response has been largely neglected. This study uses a strategy of cantilever beam tests to categorise the bending behaviour of this material and investigates to what extent through the thickness reinforcement can improve bending performance.

2 Materials

3D orthogonal woven carbon composites (provided by Sigmatex) with two variations in through-the-thickness binder density are used. Shown in **(Figure 1a)** the binder to warp stack ratio is 1:1, referred to as full TTT reinforcement in this paper, while the other reinforcement has a binder to warp stack ratio of 1:2, referred as the half TTT **(Figure 1b)**. The rest of weave parameters are kept the same, i.e. 9 weft layers and 8 warp layers giving a total thickness of 3.5mm. AKSACA A-38 carbon fibres are used with 6K fibres for the warp and weft tows and 3K tows for binder tows.

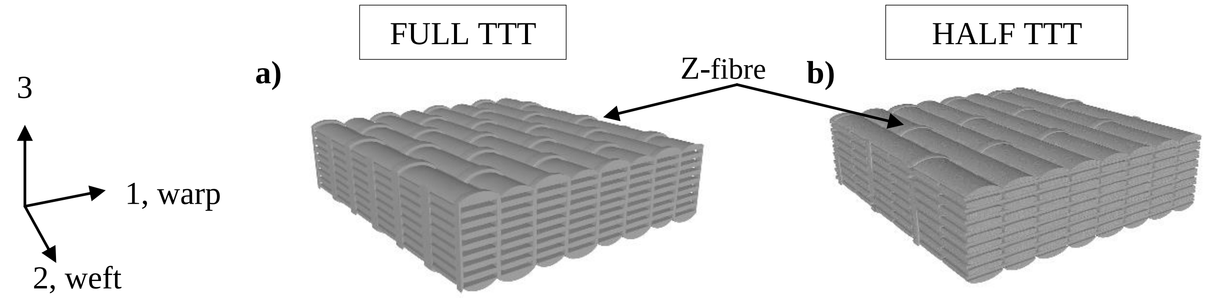

Figure 1. TexGen models of 3D woven composites (dry fabric) showing (a) full TTT reinforcement with the binder to warp stack ratio of 1:1 and (b) half TTT reinforcement with the binder to warp stack ratio of 1:2.

Epoxy resin Prime 20LV of ratio 26:1 resin to slow hardener by weight was used. Standard vacuum infusion technique was utilised for resin transfer and the panel was cured for 7 hours at 65ºC. Cantilever beam tests of both materials were tested. Electron microscope images were used in order to obtain the geometry for the tows. The warp tows have a width of 1.7mm and a thickness of 0.177mm. The weft tows have a cross section of width 1.4mm and a thickness of 0.23mm. The TTT reinforcement has as cross section width 0.5mm and thickness of 0.1mm.

3 Material Testing

Uni-axial mechanical tests **(Figure 2)** were conducted on the full TTT reinforcement composite material in order to determine material properties along the 0-90º fibre orientation.

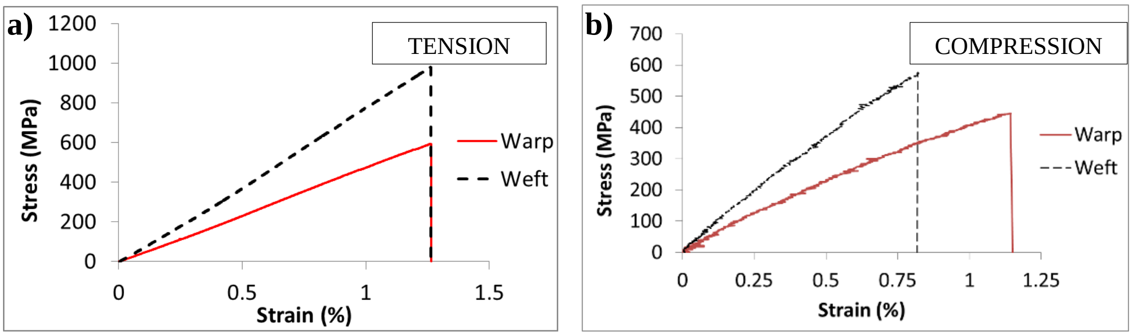

Figure 2. Stress-strain relationship of full TTT material warp and weft directions of a) Tension; b) Compression

The ±45° fibre orientation tests (**Figure 3**) were undertaken in order to obtain matrix properties as these tests are dominated by the shearing of the matrix.

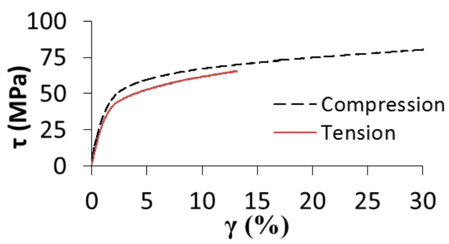

Figure 3. Shear stress-shear strain for ±45° orientation tests, showing results of both compression and tension.

4 Cantilever Beam Test

4.1 Experimental Set-Up

Cantilever beams of width 20mm with varying lengths were cut from the composite material. The beams were fixed into a rigid stainless steel fixture with M6 bolts. This fixture was subsequently bolted onto an I-Beam for stability. An Instron test machine provided a constant quasi-static displacement of 4mm/min. The set-up is shown in **Figure 4**.

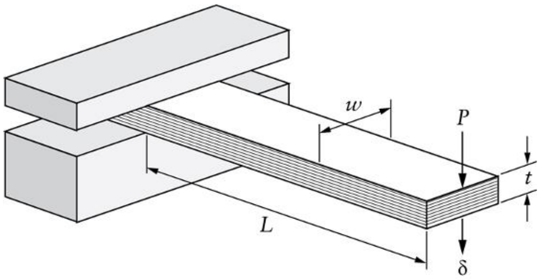

Figure 4. Sketch of cantilever beam test set up. L=7-110mm, t=3.5mm, w=20mm, roller diameter=10mm.

A camera DIC system was employed, using a telecentric lens, to measure the deflection. Load was measured directly from the Instron rig.

4.2 Elastic results

Through plotting the beam compliance versus beam length, a transition from bending governed deformation to shear governed deformation can be seen in **Figure 5.**

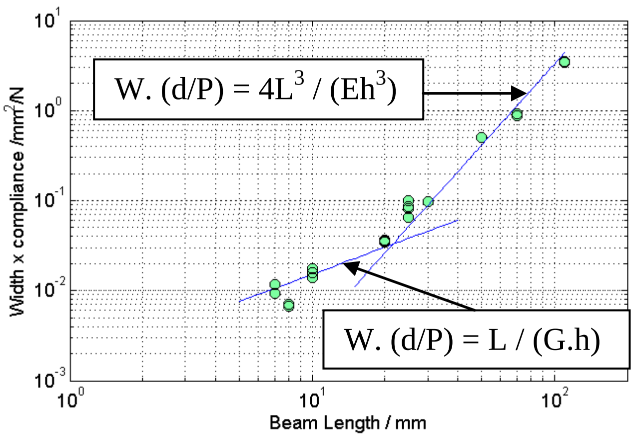

Figure 5. Width x compliance against beam length showing two regimes of shear and bending for cantilever beam tests. The out of plane shear-modulus, G_{13}, can be calculated as 3 GPa from the graph.

4.3 Long beam (40mm) results

The long cantilever bending tests are governed by the bending failure mode. In **Figure 6**, post the peak load, a large tensile crack forms at the top of the beam. This tensile crack opens at the boundary between the z fibre and matrix. This is shown with visual images taken during testing procedure. It can be seen that as there is no delamination and failure is tensile fracture of tows.

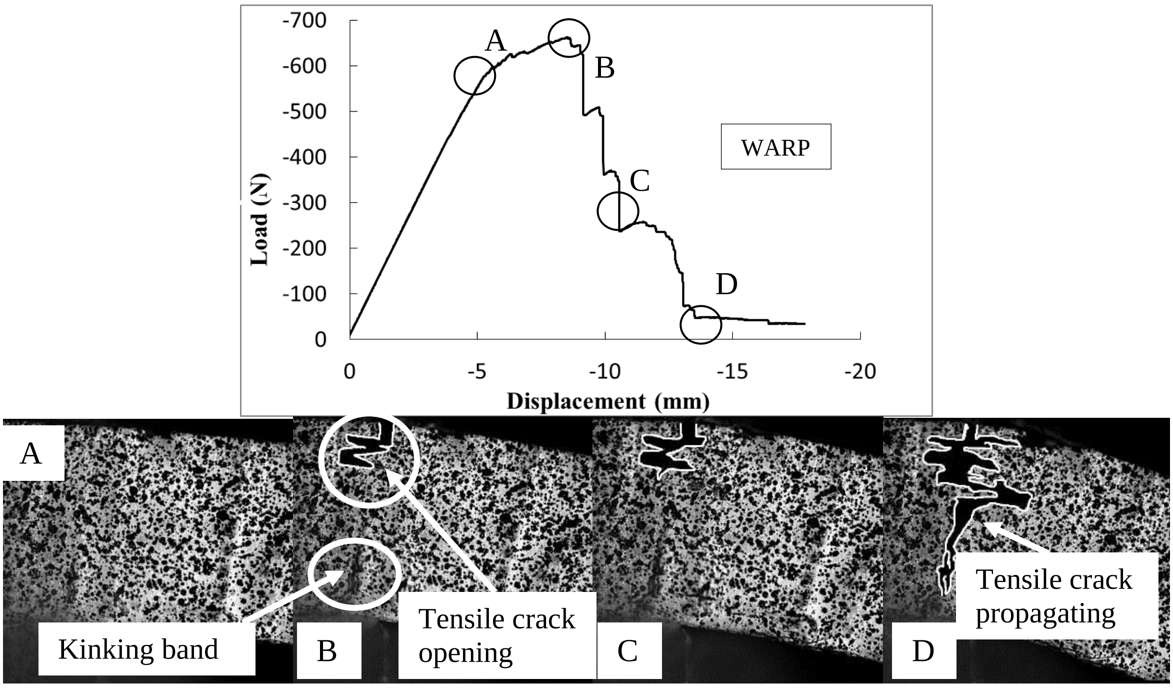

Figure 6. Long beam (40mm) full TTT cantilever test along warp direction, spot paint used for DIC

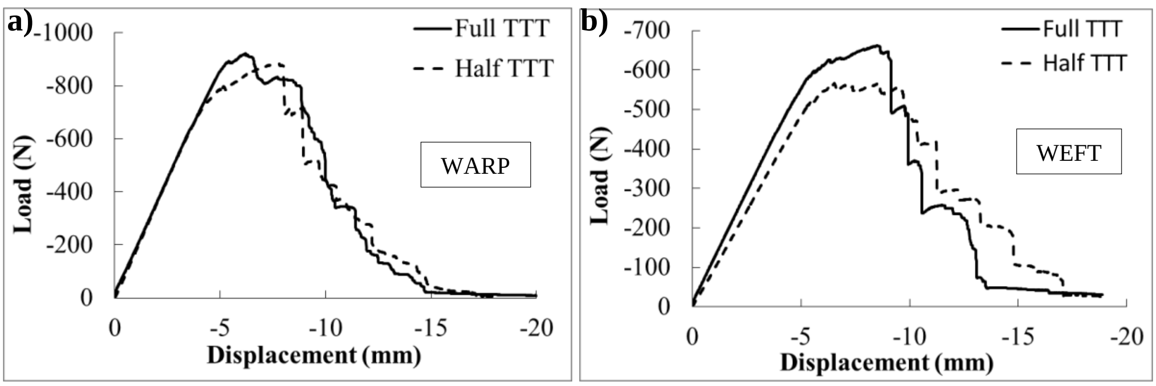

Figure 7. Long beam cantilever test load-deflection a) Warp direction b) Weft direction

From **Figure 7**, it suggests that the z binder density has negligible influence on the bending behaviour for long beam test. The stiffness and failure mode are identical, with slightly lower peak load, for Half TTT compared with Full TTT composites.

X-ray µCT scan (**Figure 8**) of a long beam test (beam length 110mm) was taken to confirm the failure mode. It should be noted that tensile cracks are formed at the z-binder interface at the top of the beam, and propagates down.

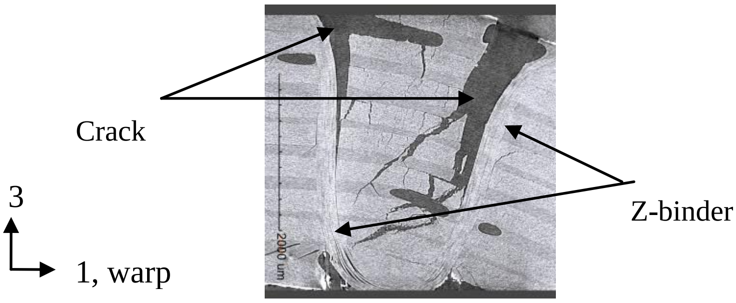

Figure 8. µCT image of long beam cantilever test showing large bending cracks forming at the edge of z-fibres.

4.4 Short beam (7mm) results

The shorter beams fail in shear. This can be seen in the images of the damage mechanisms during testing shown in **Figure 9**. The shear failure mode is predominantly matrix cracking leading to delamination. The test setup allows for quantifying the shear strength and failure mechanisms for 3D woven reinforced composites. The first peak load represents the onset of delamination. The subsequent rise in load is due to the large deformation of the beam allowing the delaminated plies to resist load. The delaminated plies then buckle; shown between photos C and D. This occurs until ultimate loss in load baring capability.

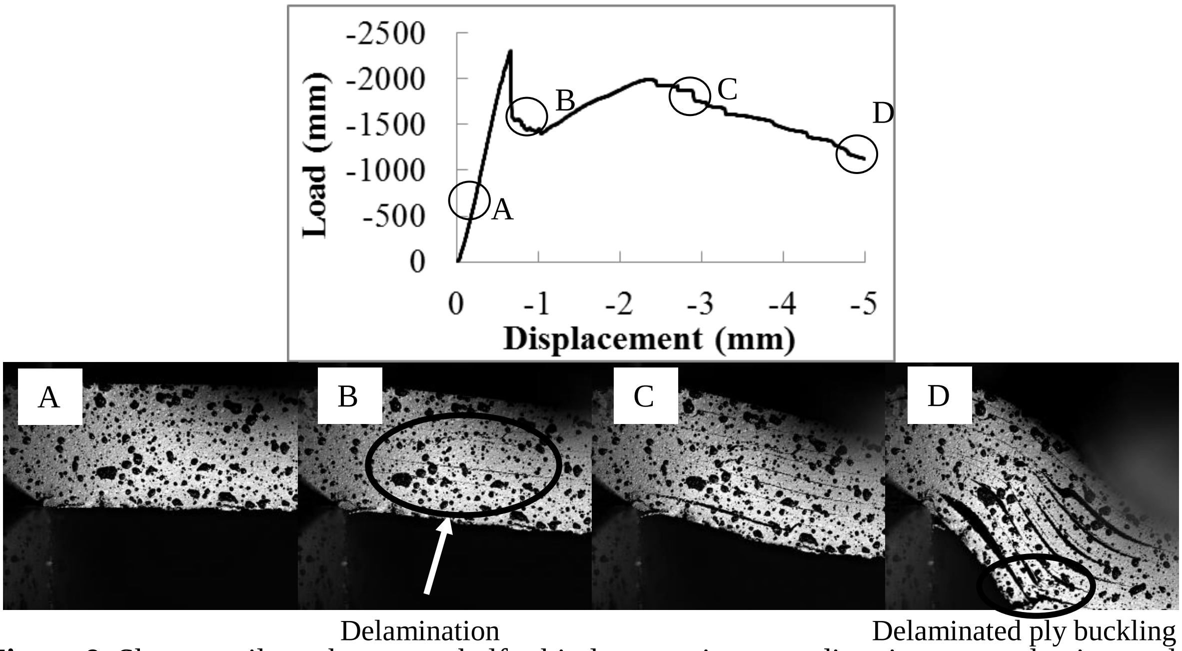

Figure 9. Short cantilever beam test half z-binder quantity warp direction, spotted paint used for DIC.

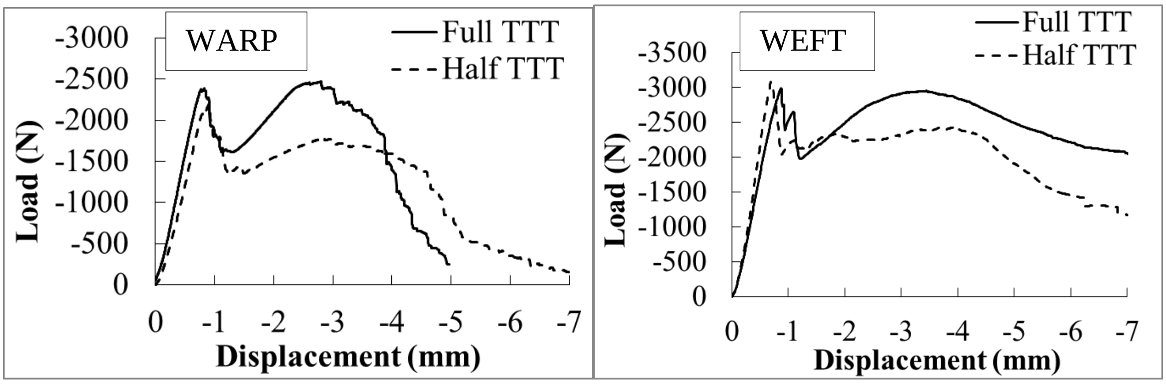

Figure 10. Short cantilever beam test load-deflection a) Warp direction b) Weft direction

In **Figure 10**, it can be seen the stiffness and the initial peak load of the short beam are identical for Full TTT and Half TTT composites. In the warp direction, the z-fibre allows for delamination containment of the beam, due to crack bridging. This causes a more sudden onset of failure, in the form of a large tensile crack opening up. The Half TTT beam simply fails as delamination continues to increase. In the weft direction, the difference shares the similar trend. The Full TTT reinforcement allows for a greater load carrying capability in the second peak. This is because the z-fibre resists the final ply buckling failure mode. The CT scan (**Figure 11**) confirms the proposed failure modes.

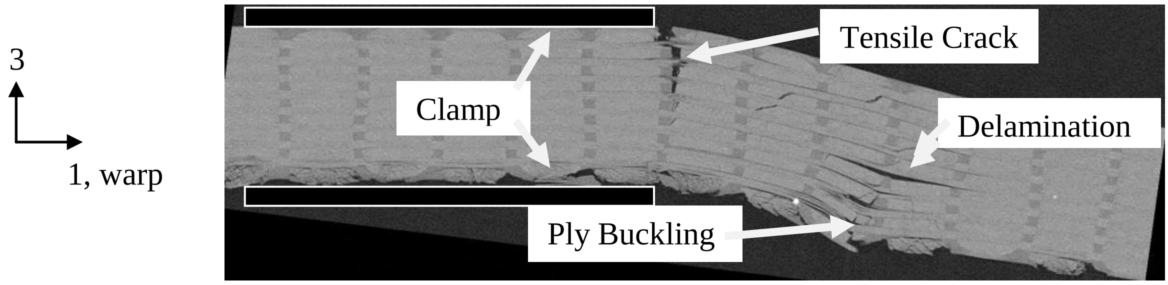

Figure 11. CT scan short beam warp direction

3.3 UD laminate comparison

Long (40mm) and short (8mm) cantilever beam bending results are now presented in **Figure 12** and **Figure 13** respectively for comparison of failure mechanisms to 3D woven composites. Material used is symmetrical 0-90° plies of 8 total layers giving a thickness of 5.16mm. Note: due to differing material geometry a quantitative comparison cannot be made, only of failure mechanisms.

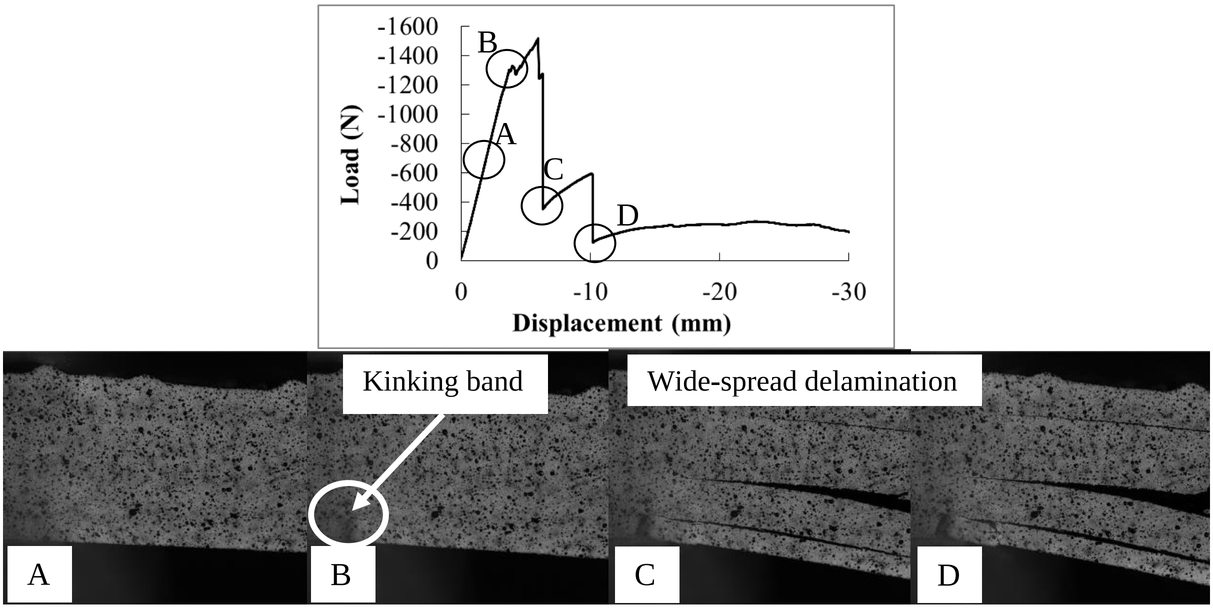

Figure 12. Long (40mm) cantilever beam test UD laminate, showing wide-spread delamination failure mechanism.

In **Figure 12**, a kinking band is formed at point B, causing a reduction of stiffness. Post peak load, wide-spread delamination occurs. No tensile cracks are formed at the top surface. This failure mechanism differs from the 3D woven material, as there is no TTT reinforcement to provide containment from delamination.

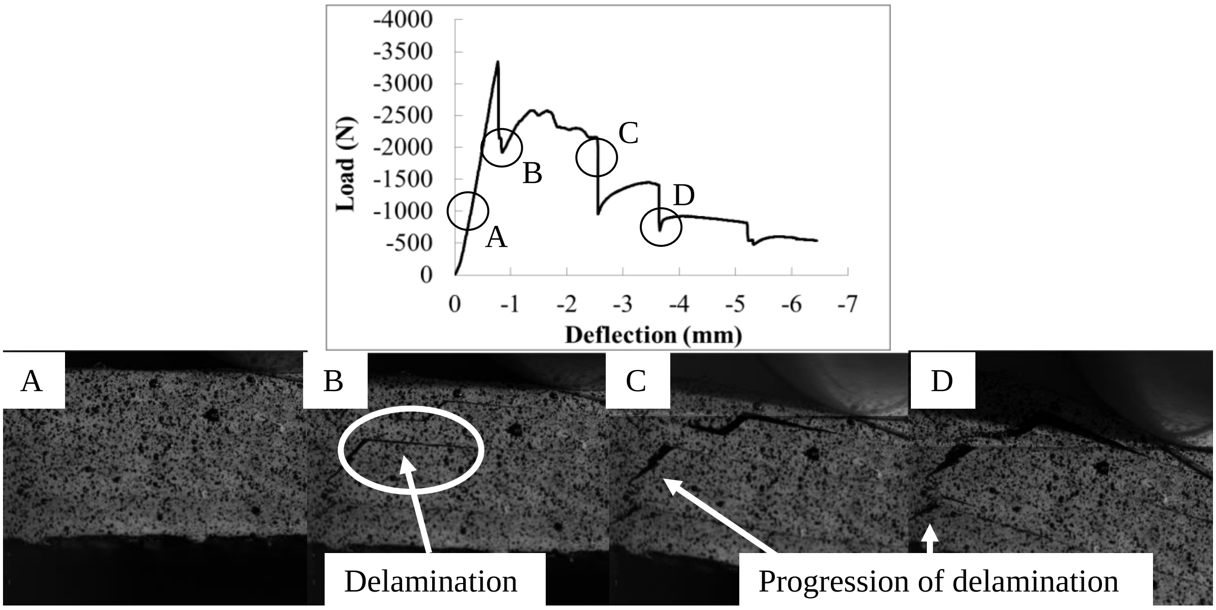

Figure 13. Short (8mm) cantilever beam test UD laminate, showing no kinking band, and shear cracking leading to delamination.

5 Conclusions

The failure mechanism during long beam bending tests of UD laminate has been shown to be different to 3D woven material. For UD laminate, wide-spread delamination is the failure mechanism. For 3D woven, the TTT reinforcement containment allows for a resistance to delamination, causing an increase in energy absorption post initial peak. During long beam cantilever tests, the density of through the thickness reinforcement tested has no influence on bending behaviour. In short beam cantilever tests (shear governed deformation) there is seen to be distinctive difference with an increase in load baring capability and energy absorption post initial peak load. This is due to the through-the-thickness reinforcement providing containment for resisting delamination and final ply buckling.

6 Further work

High velocity soft impact tests using metal foam projectiles will be undertaken on both binder densities of 3D woven carbon composite material to investigate if impact performance is affected by binder density. A high speed camera will measure the back-face deflection and the response from the two different binder densities will be compared. Post impact, cantilever beams will be cut from the samples and bending performance tested. **Figure 14** shows a preliminary comparison of 3D woven composite showing increased performance over a $[0/90]_{15}$ UD laminate when loaded with the same projectile momentum per unit area. Back face deflection , u, and time after impact, t, are normalised for comparison. L is half the beam length.

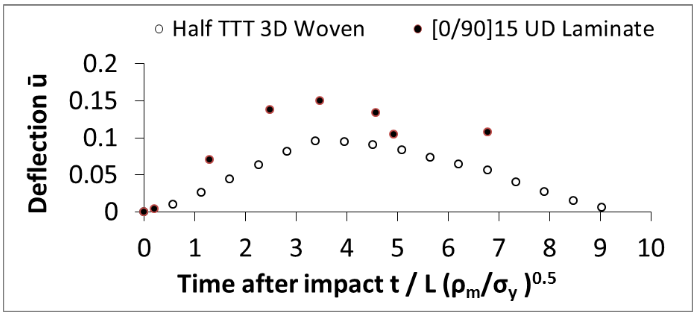

Figure 14. Mid-span deflections of the monolithic beams as a function of time for impulse, I_0 = 2.66 kPa s. Half TTT 3D Woven, studied in this paper, has a thickness of 3.5mm, length 170mm and an areal mass of 5.21 kg m^{-2}. $[0/90]_{15}$ UD laminate, described in [2], has a thickness of 3.75mm, length of 200mm and an areal mass of 5.89 kg m^{-2}.

References

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[2] B.P. Russel et al. The soft impact of composite sandwich beams with a square-honeycomb core. *International Journal of Impact Engineering* 48, 65-81, 2012.