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3D WEAVING AND CONSOLIDATION OF CARBON FIBRE T-PIECE STRINGERS

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Abstract

3D woven textile reinforced composites allow the optimisation and tailoring of specific material properties into the final component. This paper investigates composite T-section specimens for energy absorption in tensile and Quasi-static crush tests. 3D multi-layer reinforcements were manufactured on a textile loom with mechanical modifications to produce preforms with fibres orientated in the warp, weft and through-the-thickness directions. Mechanical and physical testing was then conducted to quantify the tow geometry, orientation and the effect of compaction during manufacture. The T-section specimens were manufactured using T300 800tex carbon fibre to produce a 3D orthogonal weave with six layers before impregnation with an epoxy resin system. 2D laminate layups with twelve layers were also manufactured and tested as a comparison. It was found that the 3D woven specimens provided better energy absorption than the 2D laminate specimens.

1. Introduction

New commercial aircraft programmes such as the Airbus A350, Boeing 787 Dreamliner or Bombardier C-Series have increased the demand for polymer composite primary aircraft structures, and the introduction of composites in automotive platforms has increased the use of liquid moulding resin transfer technology. This generally requires the use of a woven or stitched form of dry fabric rather than the more traditional methods of pre-impregnation of unidirectional tape. Woven textile reinforced composites allow the introduction of specific material properties into the final component that can provide a reduction in manufacturing cost. However, woven composites materials are susceptible to transverse impact loading which causes laminas to become delaminated [1]. Various methods have been developed to improve the impact tolerance including z-pinning, selective interlayers and hybrids, protective layers or resin toughening; one method that is becoming increasingly successful is to reinforce composites with a fibre that connects the layers together running from the upper to lower surface of the laminate. Mouritz et al. [2] stated that 3D woven composites have higher ballistic damage resistance and impact tolerance than 2D materials, higher tensile strain and strain-to-failure values, and also higher interlaminar fracture toughness; this might be beneficial in the design of primary aircraft structures where the limiting design criteria is compression after impact. It might also resist delaminations caused by bolt bearing loads at bolted joints or through thickness tension failure at stringer runouts. Ding et al. [3] showed that 3D composites performed significantly better in fatigue than 2D composites. Quinn [4] also points out a fundamental difference and advantage that 3D reinforcements have over 2D plied lay-up; with a 2D lay-up the orientation of the plies is carried out during the loading of the cure tool. Therefore, care and considerable time must be taken to ensure the correct orientation of the final part. With 3D woven reinforcement the orientation of the tows is controlled by the design of the fabric which Mouritz et al. [2] state make it possible to create complex near net shape preforms that can be less expensive and simpler to manufacture than 2D reinforced composites. It has been suggested however, that 3D woven composites generally exhibit lower in-plane properties due among other factors, to degradation during manufacture. The reduced mechanical performance is believed to result from crimping and misalignment of the load-bearing fibres by insertion of the z-binder yarns during weaving and distortion of the 3D architecture by compaction during the resin impregnation and cure cycle [6].

Composite aircraft wings are made from carbon fibre skins with co-cured stringers. The current complex geometry required to make an efficient composite stringer for aerospace applications results in non-optimised laminate construction in the deltoid or noodle region at the foot of the stringer assembly (Figure 6). T-sections are used for many applications that involve structural support and load bearing because they are very good at resisting bending forces along their length. They are often used to join horizontal beams in the flooring structures of large vehicles, such as aircraft and ships [7]. In aircraft, they can also be used as stringers to strengthen wing and fuselage skins. In this application, the flanges are connected to the fuselage skin which is being pushed outwards by the cabin pressure; this causes a stress concentration at the deltoid, which is why the tensile test has been carried out. They are also used in the sub frames of cars. When used in this application, the T-section may be subject to a crash event, so it is necessary to investigate how this geometry will perform. Therefore, the crush tests were carried out as part of a larger test programme.

2. MATERIALS AND METHODS

For this work, both conventional 2D woven and 3D woven T-sections were manufactured so a comparison could be made of the mechanical performance. With this in mind, efforts were made to ensure a comparable thickness, fibre volume fraction and material properties across both 2D and 3D woven components. For the 3D woven component 800tex T300 carbon fibre was used for the reinforcement materials and the matrix material used was epoxy resin LY5052 as used by Soden, et al. in prevous works [8]. The 3D woven T-sections were produced on a conventional electronic Jacquard power loom using continuous fibres. The weave architecture of the 3D woven T-sections was produced using six fabric layers with four of the layers being 5-satin harness and two being plain weave layers running along the central axis. The through-thickness reinforcement was provided by the outer surface warp fibres passing through the full material thickness (figure 1). The 3D multi-layer woven reinforcements were designed using the X-Sectional design system to provide a representation of the structure, detailing the relative positions of the yarns and also generating the lifting plan to operate a Jacquard controlled loom. Fabrics were then manufactured on a conventional textile loom with mechanical modifications to allow the addition of z-binder yarns and limit fiber damage. Reinforcements with fibers orientated in the warp, weft, and through-the-thickness directions were produced. The loom used was a Dataweave loom with Jacquard controller incorporating 1152 hooks. For the manufacture of the fabric the fiber bundles were initially rewound from large bobbins supplied by the fiber manufacturer onto smaller packages for addition to the creel (Figure 3). A high speed single head winder was used. Each package was placed on the creel and the fiber was passed through ceramic guides on the creel. The warp stuffer ends were doubled up at the ‘creel eye,’ which are ceramic guides at the end of the creel that were installed to limit entanglement of fiber bundles. Passive tensioning devices were added to each bobbin to apply tension to each warp stuffer yarn. This reduced the chances of individual tows becoming entangled before the eye board, and to aid in the movement of binders past one another in the harness (hooks).

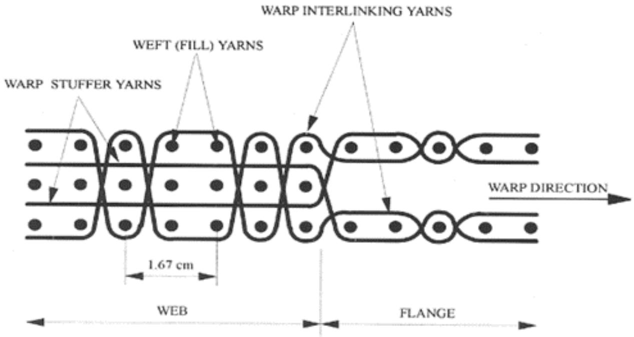


Figure 1 – Typical weave cross section used for the manufacture of 3D woven T-sections (McIlhagger, et al., 1995)

The 2D T-sections were manufactured in a layup sequence that matched the 3D woven T-sections. Twelve layers of 200tex T300 carbon fibre were laid up in the sequence of four 5-satin harness, four plain weave and four satin harness. These were all placed in the 0/90 orientation to replicate the in-plane properties of the 3D woven specimens; these were cured using tooling seen in figure 2. After cure, the moulded sections were removed from the mould and cut to shape on a diamond saw. The specimens produced gave a web thickness of 3mm and a flange thickness of 1.5mm. The flange was cut to a length of 110mm and the web was 55mm in total. The tensile specimens were cut to a depth of 25mm and the crush samples were cut to a depth of 65mm. The weave architecture was observed by optical microscopy after being polished using Struers TegraPol-31 polishing equipment at 150RPM. P220 polishing media was used to remove imperfections then P800 to provide a clearer/smoother image. Water coolant was used to prevent tooling and work piece from overheating

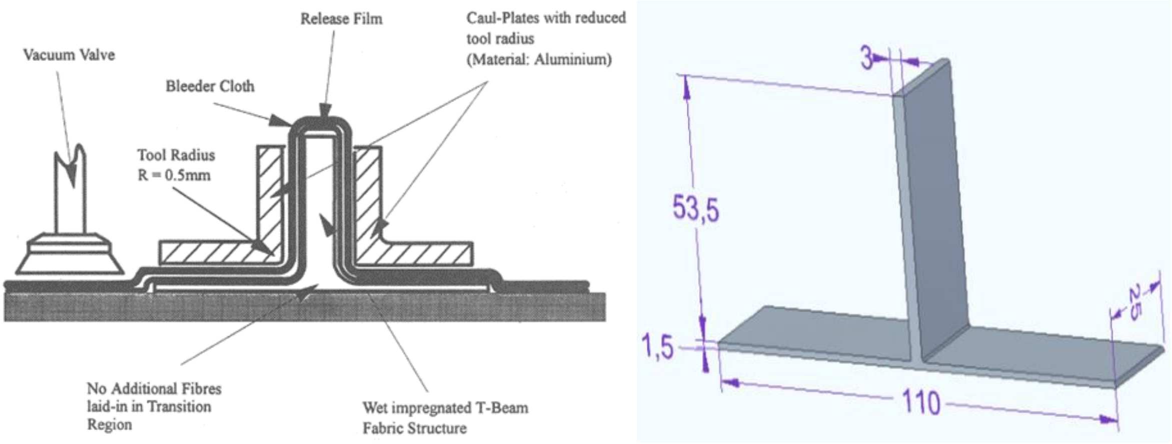


Figure 2. Tooling used to cure T-section specimens (McIlhagger, et al., 1995) and geometry of cut tensile specimens (right).

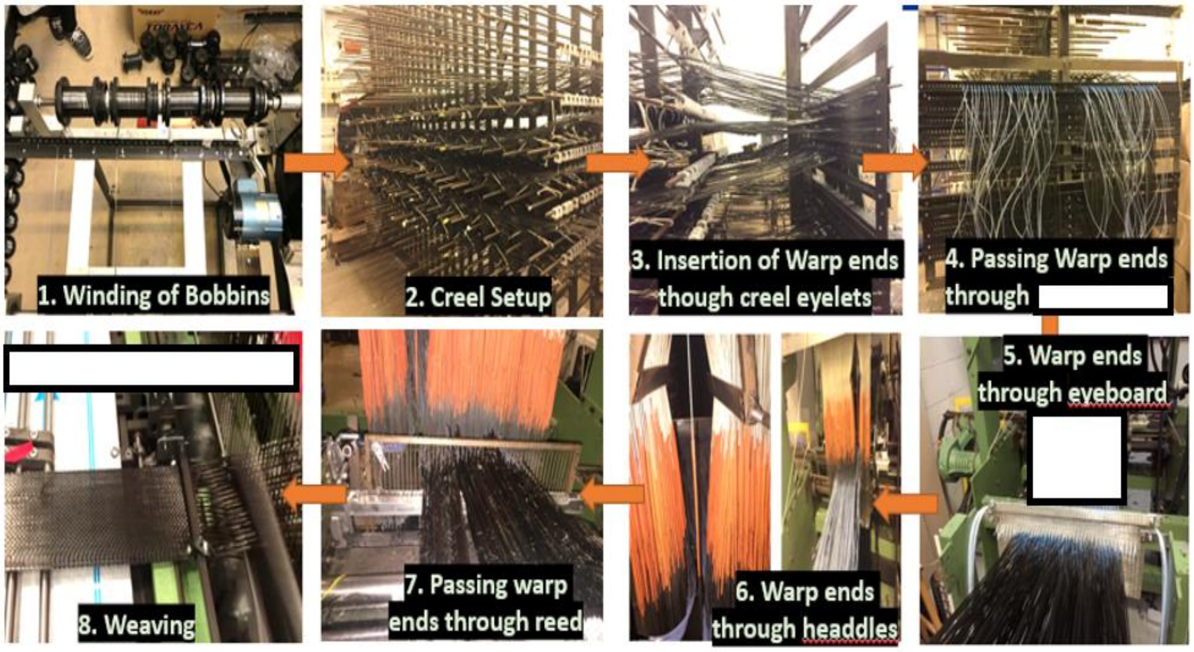


Figure 3. Stages of creel and loom setup.

Tensile testing was carried out following the ASTM standard D3039 - testing tensile properties of polymer matrix composites (ASTM, 2018). In this test, a specimen is mounted between two grips of a testing machine and loaded in tension while the force and displacement is recorded (Figure 4). The ultimate tensile strength of the material can be determined from the maximum force before failure. This test was conducted to determine the tensile properties of the T-section specimens. In this study, wedge-action grips were used and tabs had to be fitted to the specimens to reduce the chance of failure at the grips, which would render the test invalid. The depth of the grips was 50mm and the tabs used were 35mm in length and 25mm in depth; the tabs were cut from plain weave carbon fibre sheet and were bonded to the specimen, using Araldite epoxy adhesive. To measure the strain on the specimen strain gauges were fitted at areas of interest around the centre of the specimen. The tests were carried out at a loading rate of 2mm/min and sampling rate of 4Hz was used to collect tensile force data. For the strain gauges, a sampling rate of 4Hz was also used. The end of test criteria was set to be a 60% drop in peak load. The edges of the specimens were painted white to allow the crack propagation to be observed more easily (Figure 7). In this study three 3D specimens and three 2D specimens were tested.

There is no real standard for Quasi-static crush testing of composites. Therefore, in this study steps were taken to ensure each specimen was tested in the same way. Some of the testing parameters chosen were based on available literature that carried out similar testing. Crush tests are carried out to measure the energy absorption capabilities of the material in relation to crashworthiness. The specimens had a depth of 65mm. All crush specimens were tested at a loading rate of 2mm/min. In order to promote the initial failure of the specimen, triggers mechanisms were added to the specimen to providing a stress concentration. These mechanisms help to ensure that the failure observed in the specimen is stable and progressive. If a trigger is not utilised it is likely that the failure of the specimen will be unstable and catastrophic and will render the test invalid. Triggers can either be an alteration to the specimen itself by way of machining or filing, manufactured into the specimen using ply drops or an external stimulus, which separate from the specimen, such as a plug or curved crushing surface. The specimens were triggered by filing the edge of the specimen into a double bevel on to the web and each bevel was taken on to the flanges to produce a single bevel.

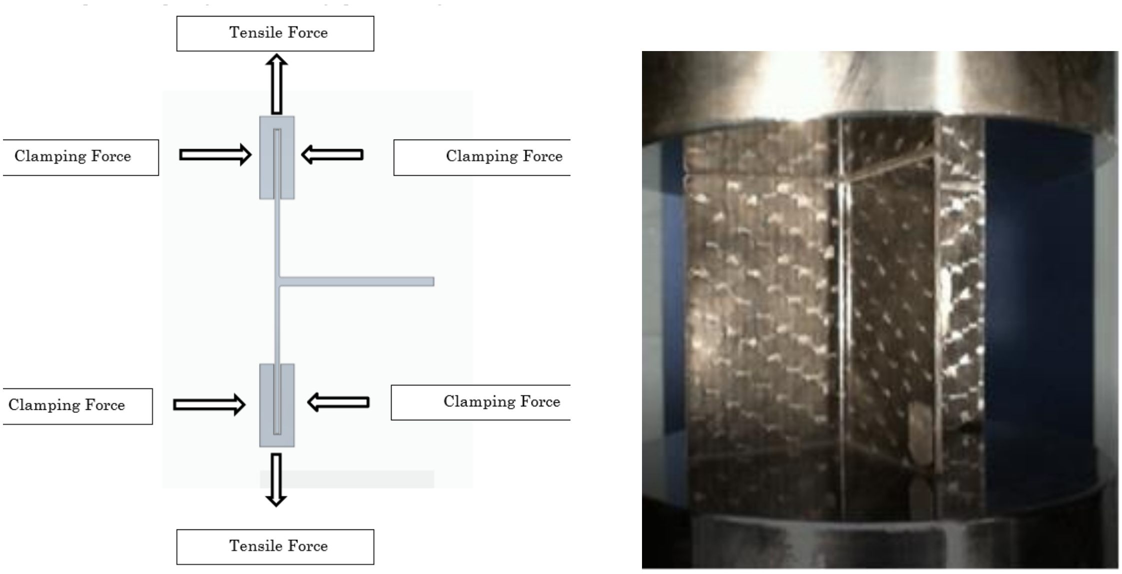


Figure 4. Tension test (left) and crush test (right).

3. RESULTS

The fibre preforms were successfully manufactured into composite specimens and were tested for fibre volume fraction using the density buoyancy method in which the sample's mass in air is recorded before weighing the sample again in distilled water according to ASTM D792-91.15 Therefore, having obtained the specific gravity and knowing the densities of the constituent parts, that is, the fiber and resin, the percentage content of the fibers was calculated. The fibre volume fraction was found to be between 52-58% across all the specimens. The micrographs in Figure 6 show the specimens to be relatively void free.

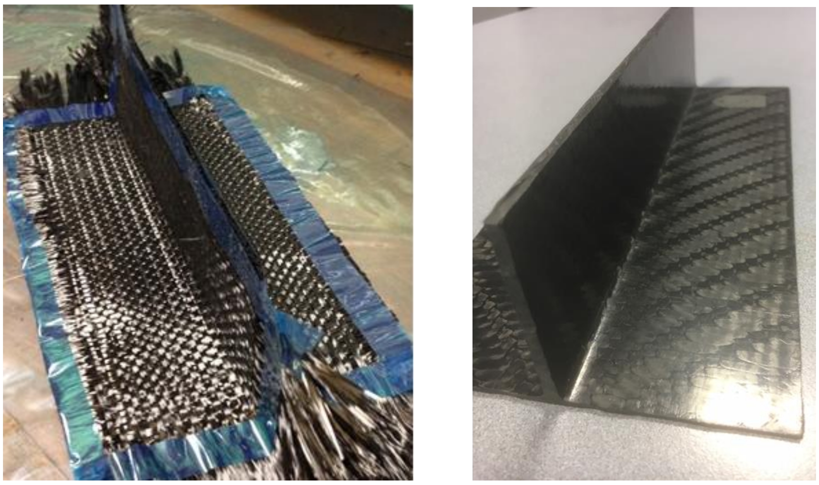


Figure 5. 3D woven preform before infusion (left) and after infusion (right).

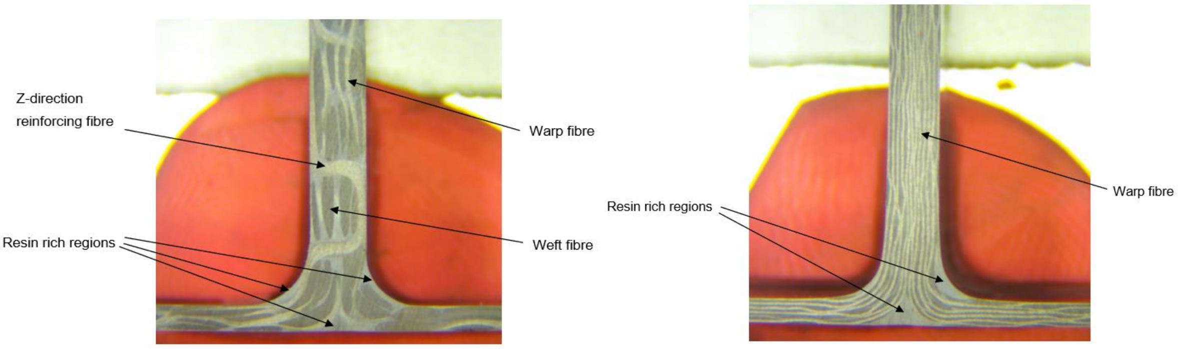
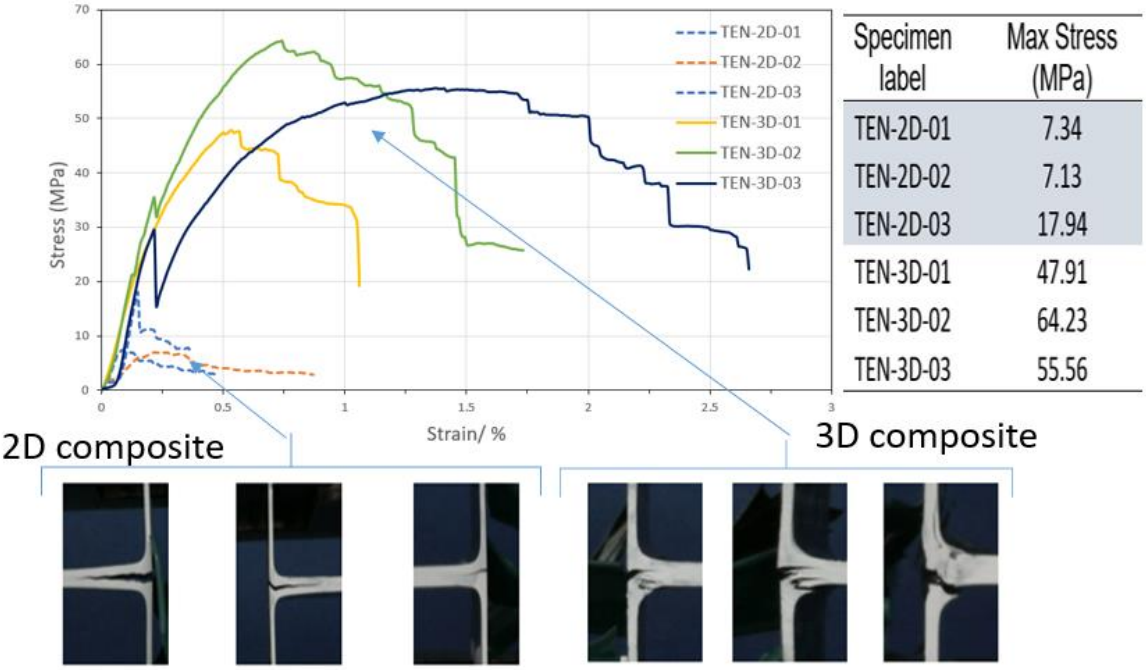


Figure 6. Micrograph image of the cross section of the 3D woven sample (left) and the 2D composite (right).

The results of the tensile tests revealed that the 3D woven composites were stronger than the 2D laminate specimens. All of the specimens exhibited similar failure modes with crack propagation through the web-flange interface; the 2D laminates suffered catastrophic delamination, whereas the 3D specimens had large amounts of fibre fracture. The presence of the Z-direction reinforcing fibres at the web-flange interface caused the 3D woven specimens to be stronger; larger forces are required to break the through-thickness fibres than are required to crack the matrix as observed in figure 7.



Specimen label	Max Stress (MPa)
TEN-2D-01	7.34
TEN-2D-02	7.13
TEN-2D-03	17.94
TEN-3D-01	47.91
TEN-3D-02	64.23
TEN-3D-03	55.56

Figure 7. Tensile results for the 2D woven sample (dashed line and left images) and the 3D woven composite (solid line and right images).

Using the data gained for each specimen for the crush tests (Figure 8), average energy absorption values, standard deviations and Coefficients of Variance were calculated. The energy absorption averages can be compared for the fibre architectures to show that the 3D specimens absorbed approximately 40% more energy than the 2D laminate specimens. This is a considerable difference and is most likely due the added stability and delamination resistance that the Z-direction reinforcing fibres gives to the 3D woven specimens, which prevented unstable failure from occurring. Very little research has been carried out into 3D woven composites, but an investigation by Goering & Bayraktar in 2016 [10] found that the best performing 3D woven composites absorbed more energy than the 2D laminates they were tested against and the results largely agree with this work.

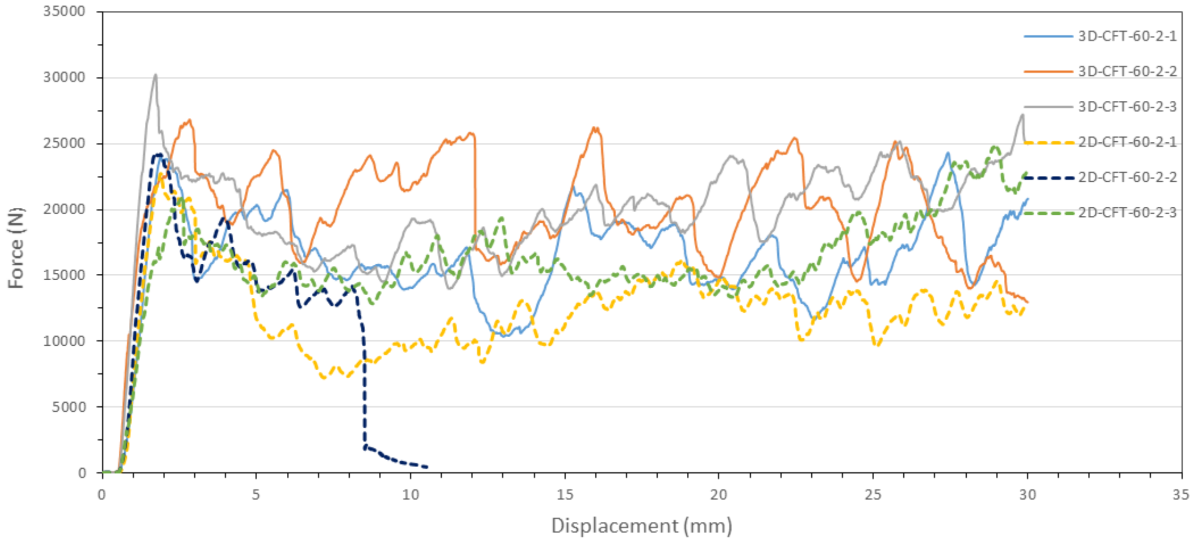


Figure 8. Crush tests for the 2D woven sample (dashed line) and the 3D woven composite (solid line).

The Force against Displacement graphs for all the specimens are characteristic of a typical crush specimen. The main difference between the 3D woven specimens and the 2D laminate specimens is that the 2D laminate specimen have a lower sustained crush force after the initial failure, due to delamination and unstable failure modes being present, which is why they have a lower total energy absorption.

Figure 9. Concepts for crash structures 3D woven by Axis Composites Ltd [11].

4. Conclusions

The tensile results revealed that the 3D woven composites were stronger than the 2D laminate specimens. The crush tests showed that when comparing 2D laminate specimens and 3D woven specimens, the 3D woven specimens absorbed more energy. This was due to the different failure modes experienced by the different fibre architectures. Research into the energy absorption of 3D woven specimens is very limited and future work into this area should focus on what 3D fibre architectures perform best in a crush type test at a range of strain rates. Although a material tested may have good energy absorption capabilities at Quasi-static strain rates, this doesn't confirm satisfactory energy absorption performance during a real-life crash incident as it occurs at much higher strain rates. Under the EU funded ICONIC programme, further work is being undertaken by Ulster University and

Axis Composites, along with the other partner organization to study and model the effect of weave architecture and component geometry on crashworthiness [12].

Acknowledgments

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