A COMPARATIVE ASSESSMENT OF 3D WOVENS AND NON-CRIMP FABRICS UNDER THREE POINT BENDING

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Abstract

Traditional 2D laminated composites are particularly susceptible to impacts, which load the composite through the thickness and generate delaminations. Various methods of through thickness reinforcement such as; z-pinning, stitching and 3D weaving have been designed to combat these loads. To comparatively assess both the in- and out-of-plane performance of leading edge resin-infused dry fiber composites, three point beam test were performed at a range of span to thickness ratios and static and dynamic loading rates. Tested materials include two tufted non-crimp fabrics and three 3D woven material systems. For high interlaminar loads 3D wovens and NCFs demonstrated comparable performance, but as the relative amount of in-plane loading was increased, the relative strength of the warp aligned 3D woven was reduced significantly. In terms of damage resistance, both tufts and through thickness warp tows had a measurable impact on the post-failure energy dissipation. Qualitatively the NCF consistently failed through extensive delamination, whereas the 3D woven showed localized matrix and fibre damage between the support and loading rollers. This fundamental change of failure behavior may have a significant effect on the way these two material systems respond to real-world impact events.

1. Introduction

Carbon fiber composites are heavily used in the aerospace industry and form as much as 50% of modern airframes by weight [1]. Unfortunately, they are particularly susceptible to damage caused by both low-velocity and high-velocity impacts. These loading scenarios load the composite through the thickness and can cause damage in the form of delaminations, fiber rupture, and matrix cracking [2]. Various composite material systems have been specifically designed in order combat these damage mechanisms. Through thickness reinforcement (TTR) in the form of, Z-pins, tufts and 3D wovens are well established, as are particle toughened resins and thermoplastic composites. Supplementary data on the relative benefits of these methods is also largely available and has been covered extensively in other studies [3], [4]. These comparisons although, are largely based on accumulations of previous results and standard material properties. Comparisons regarding impact strength are particularly hard to make given the wide range of bespoke testing equipment and testing methods [5]. The present report utilizes a three point bend test at different span to thickness ratios to examine the behavior of three 3D woven, and two non-crimp fabric (NCF) composites. This set-up allows for the simultaneous assessment of different ratios of in-plane to out-of-plane loading, and captures a variety of different failure modes that are commonly seen in impacted structures. It is extended by examining a dynamic load case using a drop tower. This provides an indication of the effect of strain rate on the material strength and failure behavior.

2. Material and Methods

The results of the study focus on the behavior of 3D woven material systems in comparison to a traditional 2D laminate made of NCF. Three 3D wovens with different fiber architectures; layer to layer (L-L), layer to layer without warp stuffers and an angle interlock (see figure 1), were kindly supplied by Sigmatex and M Wright & Sons. NCF fabrics were kindly supplied by Teijin and Saertex and were laminated into cross-ply (CP) and multi-axial (MA) layups. This enabled a direct comparison between the inherently 0/90º 3D wovens and typical multi-axial laminates. The NCF preforms were also tufted in discrete locations using a DuPont Kevlar thread and a stitch density of 3.5mm in a square array. Occasional missed or pulled out tufts were observed, but were minimal.

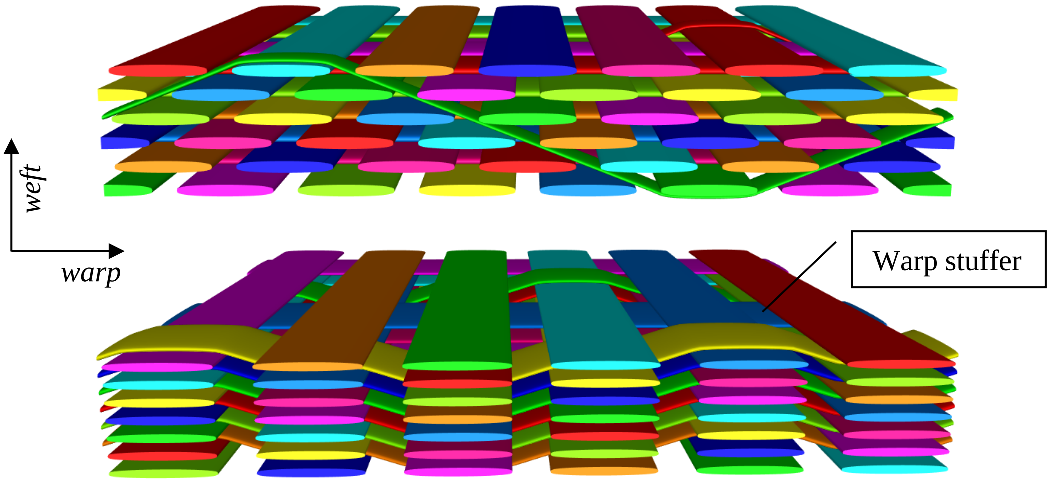

Figure 1: Schematic of the angle interlock (top) and layer to layer weave (bottom) using Texgen [6].

3D woven and NCF panels were infused using RTM6-2 in a closed mould under pressure and cured at 180º for 2 hours. The resin was injected centrally with perimeter vents. The exception being the 3D woven angle interlock which was vacuum infused due to an incompatible preform geometry. All panels were inspected non-destructively prior to machining via C-scan. Optical microscopy was also conducted in order to assess the quality of the materials, and resin burn off tests (ASTM D3171 [7]) provided an estimate of the fiber volume fraction. Further specifications regarding the material systems are listed in table 1.

Table 1: Material specifications.

	3D layer to layer warp	3D angle interlock	3D layer to layer weft	Cross-ply NCF	Cross-ply NCF tufted	Multi-axial NCF	Multi-axial NCF tufted
Resin	RTM6-2	RTM6-2	RTM6-2	RTM6-2	RTM6-2	RTM6-2	RTM6-2
Fibre	T700	IM7	IM7	IMS60/65	IMS60/65	IMS60/65	IMS60/65
Layup (% 0, 90, 45 +TTR)	0, 46, 0 54% warp	47, 48, 0 5.5% Warp	24, 46, 0 30.7% weft	50, 50, 0	50, 50, 0, 2.4% areal density	33, 57, 10	33, 57, 10, 2.4% areal density
Thickness (mm)	4	3.5	4	3.9	3.9	4	4
Vf (%)	46	56	53	53.5	53.5	55.5	55.5

Samples measured 18 by 90mm and were tested primarily using a span to thickness ratio of 8:1. This relatively low ratio (32:1 for ASTM D7264 [8] and 4:1 for ASTM D2344 [9]) was selected to simultaneously asses the in-plane and out-of-plane properties. Prior to testing specimens were labelled and prepared with a 1mm thick, 25mm long, 6082 aluminum surface tab. This was used to distribute the load and reduce localized compressive surface stresses. It was attached with double sided tape and is not believed to influence the bending behavior significantly. The specimen configuration is shown below.

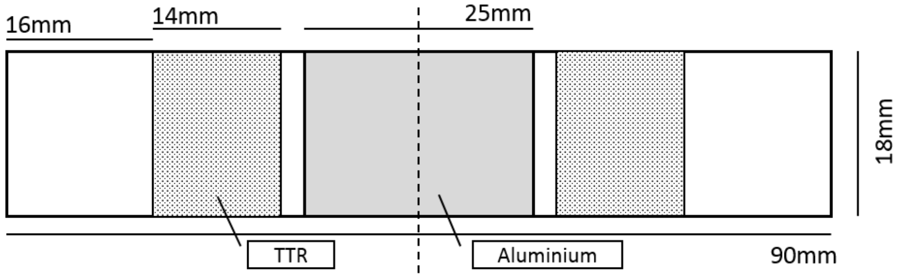

Figure 2: Specimen configuration with localized TTR and aluminum surface tab.

Testing was conducted in a three point bending configuration loaded both statically using a 10kN servoelectric Shimadzu and dynamically using an Instron Dynatup 9250HV drop tower. All static tests were recorded visually using an Imetrum Video Gauge and dynamic tests were recorded using a Photron FASTCAM SA-Z high speed camera at 25000 frames per second. A total of eight quasi-static tests (1mm/min - strain rates of ~0.0004 s^{-1}) were conducted for each material. With two trials at a span to thickness ratio of 15:1, four at 8:1 and a further two at 5:1. Eight tests at a ratio of 8:1 were also conducted using the drop tower with variable impact energies. On average impact velocities of ~1-3m/s resulted in strain rates of ~40-60 s^{-1}. Unfortunately, since the impactor falls freely on guide rails, a slight wobble was occasionally observed. This resulted in off-center impacts (±5mm) in a few of the specimens.

3. Results and Discussion

3.1 Qualitative Analysis

The NCFs failed consistently through matrix cracking followed by delamination propagation through the entire span. The multiaxial NCF exhibited far fewer complete delaminations than the cross-ply NCF. This is expected given a lower bending stiffness mismatch between plies. In the tufted NCF specimens, delaminations were completely suppressed and localized fiber damage occurred on the upper surface. However, at higher spans delaminations were found to propagate through the tufts opening under what appeared to be mode I dominated mixed mode loading.

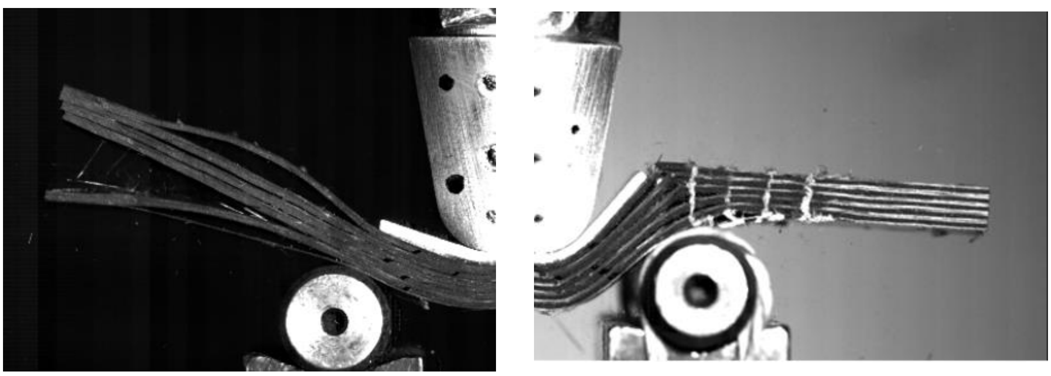

Figure 3: Primary failure mode of the cross-ply NCF (left) and the tufted cross-ply NCF (right) under a dynamic impact.

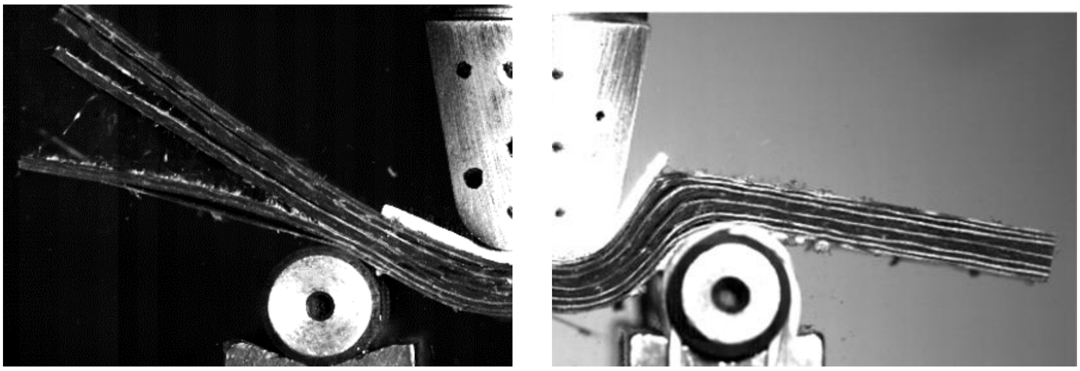

Figure 4: Delamination suppression of the multi-axial NCF (left) and the tufted multi-axial NCF (right) under a dynamic impact.

The angle interlock 3D woven showed a similar response with initial delamination growth that was completely suppressed by through thickness warp fibers. The presence of centrally constrained delaminations allowed these material systems to deflect in excess of 10mm in the static load case and provided load bearing capability well beyond initial material failure. These materials also exhibited a reverse bending behavior in the partially delaminated span which is most likely a result of a shift in the shear stress profile. In contrast, layer to layer 3D wovens failed through localized shear, and a combination of matrix damage, fiber damage and delaminations. Delaminations were suppressed to the extent that ultimate failure occurred at a lower displacement and as a result of complete through thickness material failure.

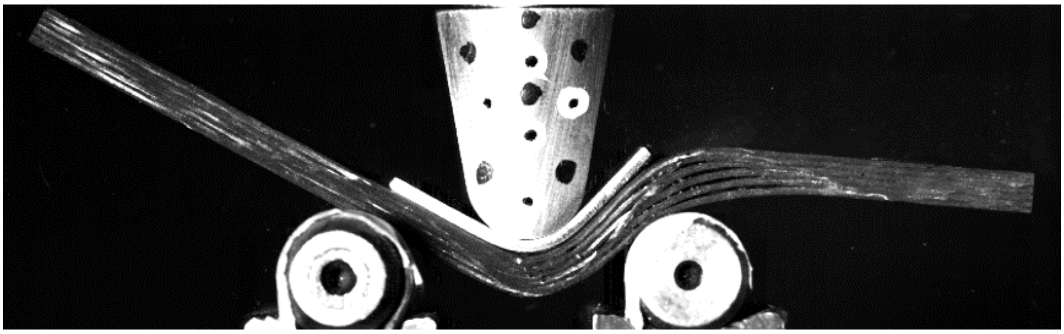

Figure 5: Constrained delamination propagation in angle interlock 3D woven, under a dynamic impact.

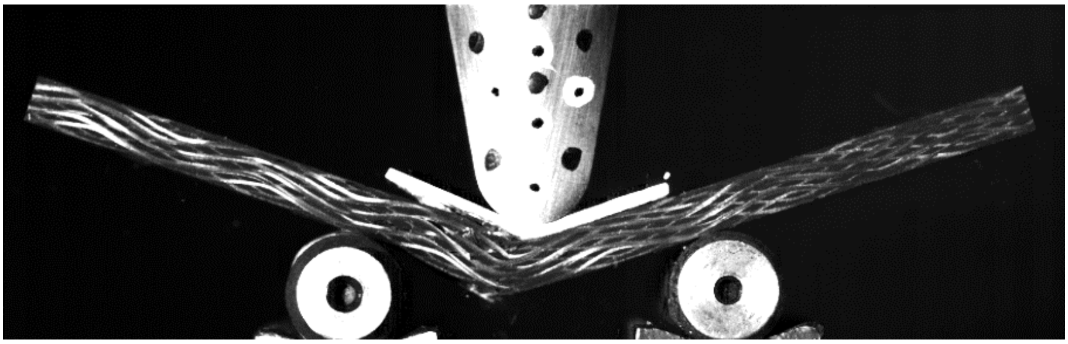

Figure 6: Through thickness failure of layer-layer 3D woven (warp) without straight stuffers, under a dynamic impact.

3.2 Quantitative Analysis

3.2.1 Failure Force

Quantitative analysis is based on load displacement curves obtained from the static and dynamic load cells. All material systems were characterised by an elastic loading portion followed by a sudden load drop and damage propagation. The failure load is defined as the maximum force reached before the first load drop (see figure 7). Unfortunately, the drop tower load cell is affected by the inertial oscillations of the impactor and the coupon assembly. However, despite these oscillations, the expected behavior is evident.

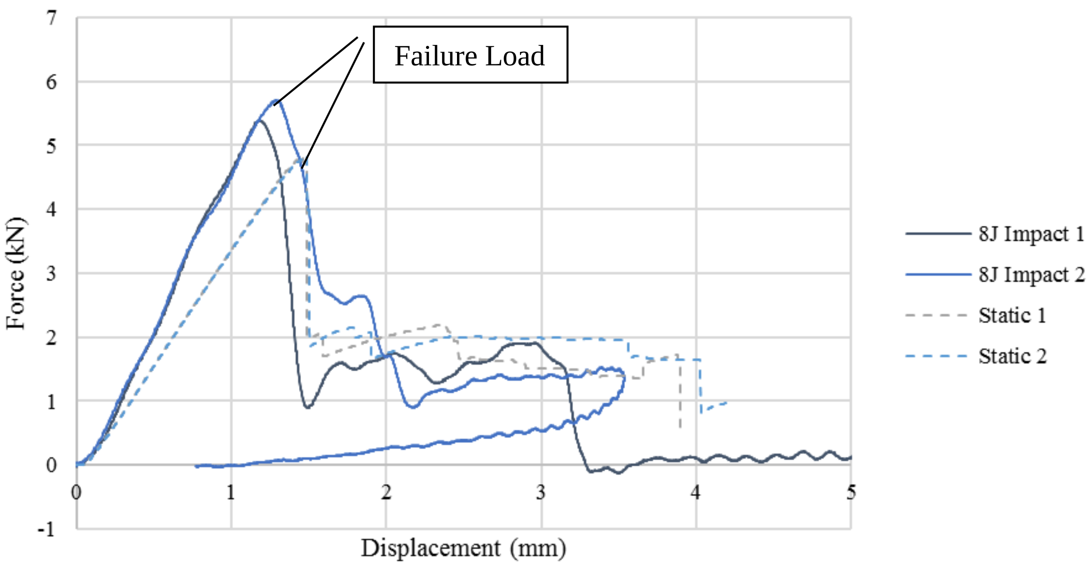

Figure 7: Representative force displacement cures for the cross-ply NCF (un-tufted), under static and dynamic loads.

As most of the tested materials failed through delamination, the load values may be related to the apparent interlaminar shear strength (ILSS) of the materials. However, given that the set-up uses non-standard span to thickness ratios, this failure load may be influenced by in-plane tensile and compressive stresses, especially at higher spans. The effect of changing the span to thickness ratio on the failure load is captured in figure 8.

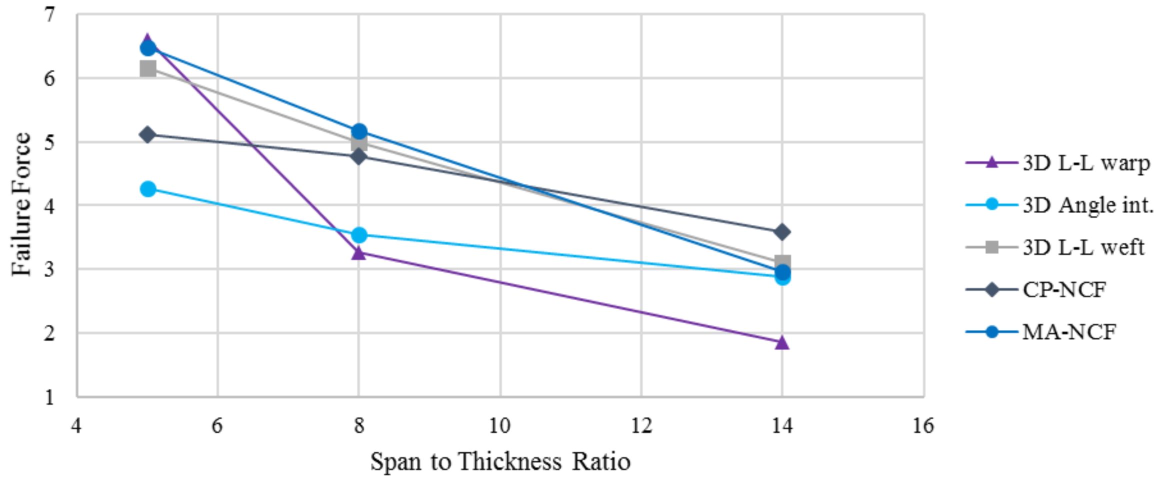

Figure 8: Critical failure force at different span to thickness ratios.

From figure 8, the multi-axial NCF and 3D woven (weft aligned) are best performers across the majority of the tested range. However, in 3D woven (warp aligned) rapidly loses strength as the ratio of in-plane stresses is increased. This is most likely an effect of the higher crimp and waviness in this direction. Previous studies have reported similar findings with higher bending strengths and stiffnesses for layer to layer weaves in the weft direction [10].

Considering a set span to thickness ratio of 8:1, we may also examine the effect of loading rate on the measured failure force. This is shown in figure 9.

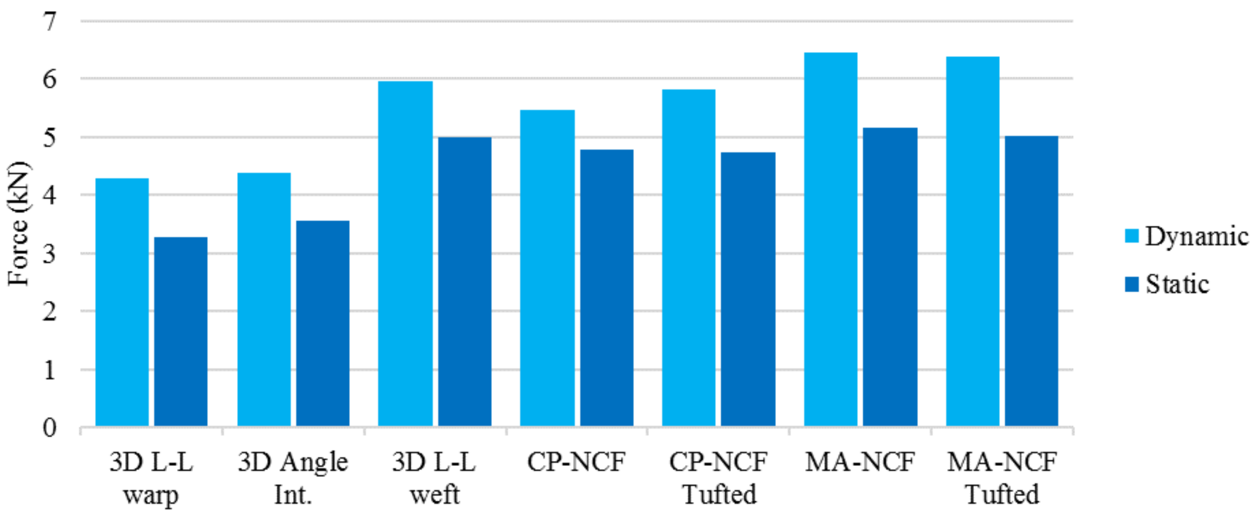

Figure 9: Recorded failure force at 8:1 span to thickness ratio for static and dynamic tests.

Although static load curves were largely similar to the dynamic equivalent, the failure loads and the flexural modulus were consistently 15-20% lower. This indication of a rate effect is also captured in other studies where increases in strength and stiffness with increasing rate were identified for both 2D and 3D epoxy composites [4], [11].

3.2.2 Energy Dissipation

To examine the post-damage behavior of these materials tests with high displacements (up to 7mm) were examined. The total amount of energy dissipated during the impact may then be calculated by taking the integral of the force displacement curve. The energy may further be categorized as being either; initially stored though elastic deformation (initiation energy) or dissipated through progressive damage development after the initiation of failure. By taking a ratio of energy dissipated in failure to the initiation energy, a so called "ductility index" may be defined [5]. Figure 10 details both the statically/dynamically absorbed energies as well as static/dynamic ductility ratios.

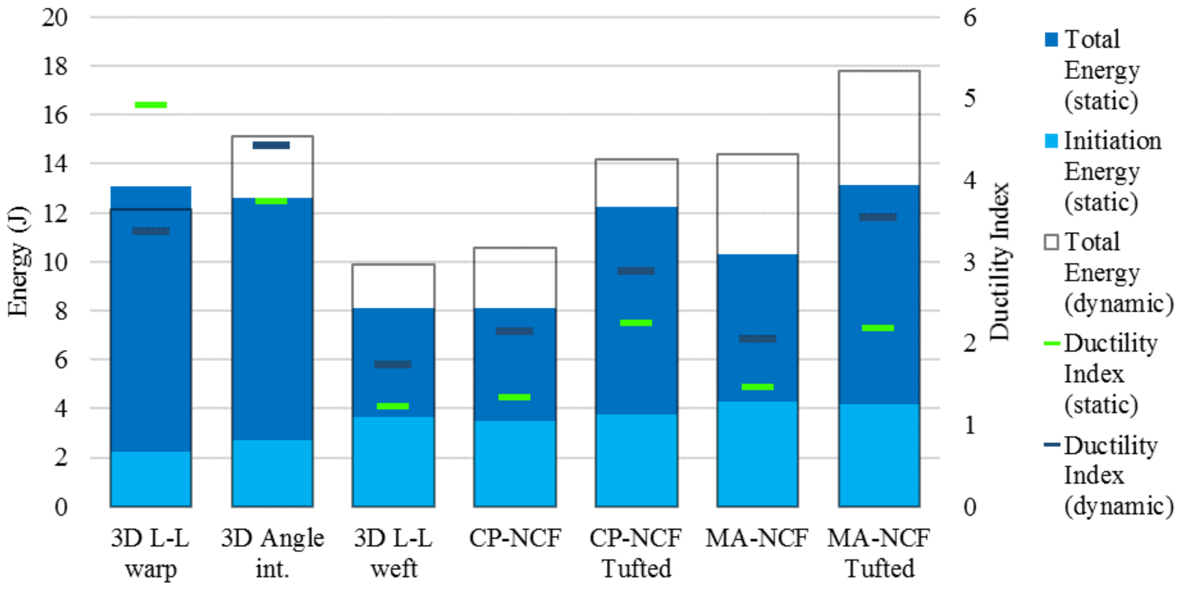

Figure 10: Absorbed energy and ductility ratios for static and dynamic tests.

Focusing on the static test data, the best performing material systems are the warp aligned 3D wovens and the tufted NCFs. Here there is a noticeable benefit of TTR on the system's capacity to dissipate energy after initial failure. This comes without an adverse effect on strength and stiffness, as TTR bands are placed at discrete locations targeting delamination propagation and not initiation. 3D woven materials were found to be highly affected by the orientation (warp/weft) and weave architecture. Specimens tested along the warp direction showed the highest ductility ratios, whereas the weft orientated layer to layer weave exhibited the lowest capacity for energy dissipation. This behavior has been observed previously [12] and may be attributed to increased fiber interlocking in the warp direction and tendency for local damage in the weft. Although, given the wide range of other factors (weave architecture, fiber type, fiber volume fraction and manufacturing method) this conclusion is subject to further verification.

Energies dissipated under quasi-static loading are for the most part lower than that in the dynamic case. This is expected given the lower stiffness and strength for all materials and consequently lower potential for elastic energy dissipation. However, the warp aligned layer to layer demonstrates an increased capability to dissipate energy under static loading despite this effect. It is believed that this is a result of the high degree of through thickness fiber interlocking restricting the growth of delaminations. While in the quasi-static set-up the low rate of loading may not restrict the propagation of interlaminar damage, the speed of a low low-velocity impact may prevent delaminations from reaching their full extent before secondary failure modes such as tensile fiber failure are triggered. This reduced ability to absorb damage in interlaminar failure modes may account for the relatively lower capability for energy dissipation under impact.

4. Conclusion

A three point bend test has been selected to replicate key failure modes observed in low-velocity impacts. The results of the study may be used to screen competing materials systems based upon their combined bending strength and post-failure damage tolerance. Two tufted non-crimp fabrics (NCFs) and three 3D wovens, were tested at a range of span to thickness ratios and loading rates. It was found that for the majority of the tested span to thickness ratios, both the NCF's and the weft aligned layer-to-layer weave demonstrated the highest failure loads. In terms of damage resistance, the warp aligned 3D wovens and tufted NCFs showed the highest ability to dissipate energy through progressive failure mechanisms. While the 2D laminated NCFs failed through extensive delamination, these were effectively constrained or suppressed in tufted and 3D woven materials, resulting in high displacements and localized damage. Through the combination of both quantitative data and qualitative observations of the material responses, this study may therefore inform the material selection process for product development programs.

Acknowledgments

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References

[1] "Growing demand for eco-efficient aircraft," *Reinf. Plast.*, vol. 56, no. 6, pp. 36–37, 2012.
[2] M. O. W. Richardson and M. J. Wisheart, "Review of low-velocity impact properties of composite materials," *Compos. Part A Appl. Sci. Manuf.*, vol. 27, no. 12, pp. 1123–1133, 1996.
[3] a. P. Mouritz and B. N. Cox, "A mechanistic interpretation of the comparative in-plane mechanical properties of 3D woven, stitched and pinned composites," *Compos. Part A Appl. Sci. Manuf.*, vol. 41, no. 6, pp. 709–728, 2010.
[4] R. Gerlach, C. R. Siviour, J. Wiegand, and N. Petrinic, "In-plane and through-thickness properties, failure modes, damage and delamination in 3D woven carbon fibre composites subjected to impact loading," *Compos. Sci. Technol.*, vol. 72, no. 3, pp. 397–411, 2012.
[5] W. J. Cantwell and J. Morton, "The impact resistance of composite materials — a review," *Composites*, vol. 22, no. 5, pp. 347–362, 1991.
[6] H. Lin, L. P. Brown, and A. C. Long, "Modelling and Simulating Textile Structures Using TexGen," *Adv. Mater. Res.*, vol. 331, pp. 44–47, 2011.
[7] ASTM, "Standard Test Methods for Constituent Content of Composite Materials." Designation: D3171.
[8] ASTM, "Standard Test Method for Flexural Properties of Polymer Matrix Composite Materials." Designation: D7264.
[9] ASTM, "Standard Test Method for Short-Beam Strength of Polymer Matrix Composite Materials and Their Laminates." Designation: D2344.
[10] A. M. Waas and A. Arbor, "Flexural Behavior of a Layer-to-Layer Orthogonal Interlocked Three-Dimensional Textile Composite," *J. Eng. Mater. Technol.*, vol. 134, no. July 2012, pp. 1–8, 2012.
[11] T. Walter, "Characterization of Delamination in 3D Woven Composites under Static and Dynamic Loading," University of Florida, 2011.
[12] M. Pankow, A. Salvi, A. M. Waas, C. F. Yen, and S. Ghiorse, "Resistance to delamination of 3D woven textile composites evaluated using End Notch Flexure (ENF) tests: Experimental results," *Compos. Part A*, vol. 42, no. 10, pp. 1463–1476, 2011.