MECHANICAL BEHAVIOUR AND COMPUTED TOMOGRAPHY DAMAGE ANALYSIS OF FABRIC-REINFORCED COMPOSITES UNDER BENDING

Himayat Ullah[1]* and Vadim V. Silberschmidt[2]
[1]*CESAT, Islamabad, Pakistan, Email: uhimayat@gmail.com
[2]Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire, LE11 3TU, UK

Keywords: CFRP; GFRP; Micro CT; Damage; Bending

Abstract
Fabric-reinforced polymer (FRP) composites are increasingly employed in aerospace structures and sports products. In these applications, they are usually subjected to large-deflection quasi-static and dynamic bending deformations. Such loading conditions induce damage within the material at various scale levels affecting their strength, stiffness and energy-absorbing capability. For this purpose, mechanical behaviour of woven carbon and glass fabric-reinforced polymers (C/GFRPs) composites in on- and off-axis orientations is first quantified by carrying out large-deflection quasi-static bending tests followed by dynamic ones employing an Izod type impact tester. The obtained stress-strain and force-deflection plots showed CFRP laminates fractured due to brittle carbon fibres. The off-axis CFRP and both the on- and off-axis GFRP samples showed damage and nonlinearity at low impact energy with residual load carrying capability. Further, off-axis laminates of both materials and on-axis GFRP absorbed more energy without fracture by manifesting permanent deformation. Micro-computed tomography (micro-CT) analysis of the tested CFRP specimens showed that matrix cracking, delamination, tow debonding and fabric fracture were the dominant damage modes. Further, a catastrophic brittle fracture was observed in the CFRP on-axis laminates whereas the off-axis laminates exhibited pseudo-ductile behaviour thanks to matrix cracking and fibre trellising before their failure at higher energies.

1. Introduction

Fabric-reinforced composites (FRCs) have found an ever increasing application in various industries due to their unique properties such as excellent stiffness, high strength-to-weight ratio, high impact strength, good resistance to fracture and ease to manufacture shapes tailored for specific applications [1, 2]. Hence, they are now broadly used in aerospace industry; there is an increasing use of them in sports products. In service, these composites structures can be exposed to large-deflection quasi-static and dynamic bending loads. Such loading can cause deterioration of structural integrity and load-bearing capacity due to induced damage. Because of their heterogeneity and microstructure, composite laminates usually demonstrate multiple modes of damage and fracture than their macroscopically homogeneous metallic counterparts. Among damage and fracture modes are fibre breaking, transverse matrix cracking, debonding between fibres and matrix and inter-ply and intra-ply delamination delamination [3]. Further, due to inherent brittleness of carbon fibres, CFRP laminates fail suddenly without giving any prior warning. Despite their high specific strength and stiffness, these materials do not exhibit ductile behaviour like metals; thus compromising energy absorption and residual load carrying capability requiring high safety margins [4]. Development of ductile composite materials can extend their applications to various industries such as aerospace, sports, automotive and construction.

The quasi-static and dynamic bending loads induce various modes of damage in woven composites such as matrix deformation and micro-cracking, fibre breakage, tow-matrix debonding, interplay and intra-ply delamination and fabric fracture [5]. Impact damage especially delamination significantly reduce the material's strength and stiffness, degrading its structural integrity. Therefore, it is important to study damage imposed in composites by quasi-static and dynamic bending conditions. Realisation of microstructural damage mechanisms are often barely visible and cannot be detected by simply examining the exposed surfaces of composite specimens. Internal damage modes can be analysed with X-ray micro-computed tomography (micro-CT), which has potential to provide a full-field high resolution 3D representation of internal damage modes and their coupling in composites non-destructively. This relatively recent technique was employed in [3, 6-9] to analyse damage behaviour of composites at micron scale. Therefore, in this study, damage induced in composite laminates under large-deflection dynamic bending, was investigated using micro-CT.

In this paper, the flexural behaviour of woven CFRP and GFRP laminates in warp, weft and off-axis orientations is studied first under large-deflection quasi-static bending. The experimental tests characterised the stiffness, strength and ductile behaviour of both CFRP and GFRP laminates. Dynamic bending tests are carried out at various energy levels by employing an Izod type impact tester. The tests showed that CFRP laminates fractured due to brittle carbon fibres. The off-axis CFRP and both the on- and off-axis GFRP samples showed damage and nonlinearity with residual load carrying capability. Further, off-axis laminates of both materials and on-axis GFRP absorbed more energy without fracture by manifesting permanent deformation like ductile materials. In the tested laminates, various damage modes were characterised with micro-CT technique.

2. Experimental methods

2.1 Materials

Composite laminates with two different types of fabrics made of carbon and glass fibres reinforcing thermoplastic polyurethane (TPU) matrix were studied. The 1 mm-thick specimens were produced from 0°/90° prepregs using four fabric layers designated as $[0°,90°]_{2s}$, where 0° and 90° are the warp and weft directions of tows, respectively. In this study, the stacking orders of the form $[0°,90°]_{2s}$ and $[90°,0°]_{2s}$ are designated as *warp* and *weft* specimens, respectively. Another type of laminate, where the plies' orientations are at an angle to the laminate orientation, in the form of $[+45°/-45°]_{2s}$ is designated as *off-axis* specimen. The elastic constants of CFRP and GFRP determined from the quasi-static tests are presented in Table 1; details of the tests for characterisation of both types of materials are presented elsewhere [7, 10].

Table 1. Material properties of twill 2/2 woven composites

	E_{11} (GPa)	E_{22} (GPa)	E_{33} (GPa)	G_{12} (GPa)	$G_{13}=G_{23}$ (GPa)	ν_{12}
CFRP	55.0	52.0	8.0	3.8	3.7	0.05
GFRP	21.5	21.0	8.5	3.1	4.1	0.11

2.2. Quasi-static bending tests

The quasi-static bending tests were performed at indenter speed of 100 mm/min (strain rate 0.0417 s^{-1}) according to ASTM D790 standard using the Instron 5569 machine. The obtained bending stress-strain diagrams for each orientation of CFRP and GFRP laminates are shown in Fig. 1. In both types of on-axis CFRP specimens, flexural tests of warp and weft laminates demonstrated a quasi-brittle behaviour. The reason for this material behaviour is that in on-axis laminates, the applied load is carried by the fibres, which are strong but brittle. Thus, the stress-strain curves are almost linear up to the catastrophic fracture, represented by an abrupt drop of the stress level in Fig. 1.

As shown in Fig. 1, all the GFRP and CFRP off-axis specimens demonstrated a large-deformation nonlinear behaviour before their ultimate failure as compared to the on-axis CFRP laminates. In off-axis laminates, this ductile-like behaviour is due to matrix plasticity as well as cracking and alignment of tows along the loading directions called fibre trellising. The latter is the result of fibres reorientation towards the loading direction and the angle between warp and weft fibres changes from 90° with increasing the load level. Hence, when off-axis specimens are subjected to tensile loads (as in bending), the tows with warp and weft directions rotate with respect to each other, resulting in in-plane shear deformation. However, in on-axis GFRP specimens, the ductile behaviour before ultimate failure is due to visco-elasto-plastic nature of glass fibre apart from compliant TPU matrix. Such ductile, or yielding like behaviour of composites is more desirable for energy-absorption purposes and is termed pseudo-ductility in recent research works such as [11]. Thanks to such behaviour, the GFRP and CFRP off-axis laminates are still capable to bear a load after the damage initiated at the yield point (Fig. 1). Here, the yield point refers to the knee where the stress-strain curve deviates from the initial elastic line and does not necessarily indicate the presence of plastic deformation as observed in metals. Further, the off-axis and GFRP specimens exhibited higher levels of strain to failure- than that of the on-axis CFRP specimens making them favourable for higher energy absorption. The off-axis GFRP specimen did not fracture but exhibited a permanent deformation. Although, the increase in energy-absorption capability is accompanied by a reduction in stiffness and strength properties of the tested off-axis and GFRP specimens. Still, these properties can be improved by selecting ply angles in the range from 20° to 30° depending on various applications along with glass fibres. Therefore, it is evident that off-axis CFRP and all types of GFRP laminates are capable to plastically deform and absorb energy like metals before their ultimate failure.

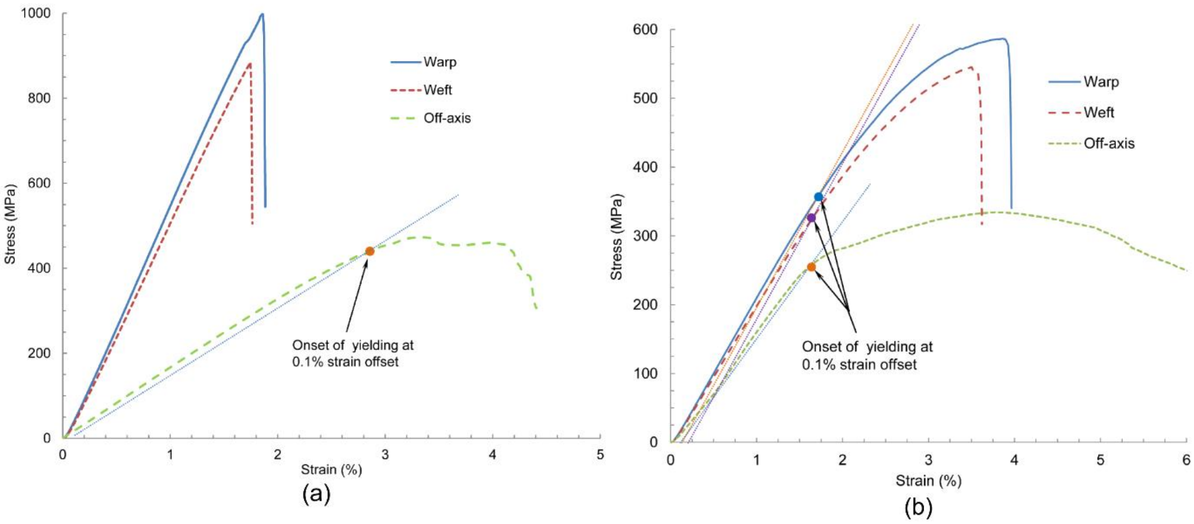

Figure 1. Stress-strain diagram from quasi-static flexural tests of twill 2/2 (a) CFRP and (b) GFRP specimens

2.3. Dynamic bending tests

Dynamic bending tests were performed to characterise the behaviour of composite laminates under low-velocity impact regimes. Here, in Izod impact test, un-notched specimens of CFRP and GFRP were tested to characterise their dynamic behaviour under large-deflection bending conditions. Dynamic bending tests in an impact energy range from 0.1 J to 1.2 J were performed according to the ASTM D4812 standard. In these tests, the bottom of the specimen was held in the fixture, whereas its upper part was struck by the impactor with specified impact energy, resulting in dynamic large-deflection flexure. A piezoelectric force sensor was fixed to the hammer's striker to measure the impact load. The data acquisition was achieved using DAS 8000 system at 227 kHz frequency.

The obtained force-deflection responses (F-d) for the warp (on-axis) CFRP and GFRP specimens at different impact energy levels are given in Fig. 2. In cases without any impact damage, a peak load relates to the maximum resistance provided by the specimen as an indication of specimen's flexural stiffness [12]. The slope of F-d curves indicates the contact stiffness, while the area inside the curve is the energy absorbed. It is clear that the energy absorbed by specimens increased with impact energy. It is worth mentioning that membrane stiffening effect also occurred in thin laminates as the maximum deflection was several times greater than the specimen's thickness. The CFRP on-axis specimens fractured at 0.6 J, while the GFRP on-axis specimens tested at energies between 0.8 J – 1.1 J exhibited a permanent bending-like deflection after testing (Fig. 2b), which may be due to the visco-elasto-plastic nature of the glass fibres apart from the TPU matrix. The GFRP specimens underwent large deformation during loading; and subsequently, a snap-back during the rebound where the striker slipped past the specimen, represented by the depths and kinks in Fig. 2b. Unlike the CFRP specimens, the peak loads remained almost the same with appreciable increase in the deformation of GFRP specimens at higher impact energies. It was also observed that GFRP laminates required higher impact energies for specified damage and failure due to their greater capacity of storing elastic energy.

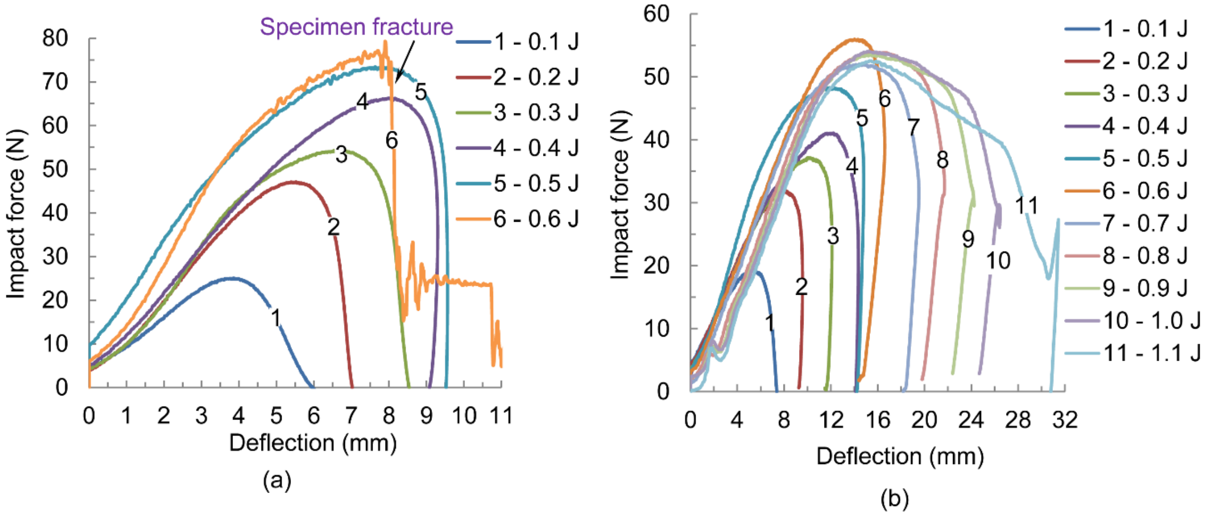

Figure 2. Force-deflection responses of warp (on-axis) (a) CFRP and (b) GFRP laminates at various impact energies

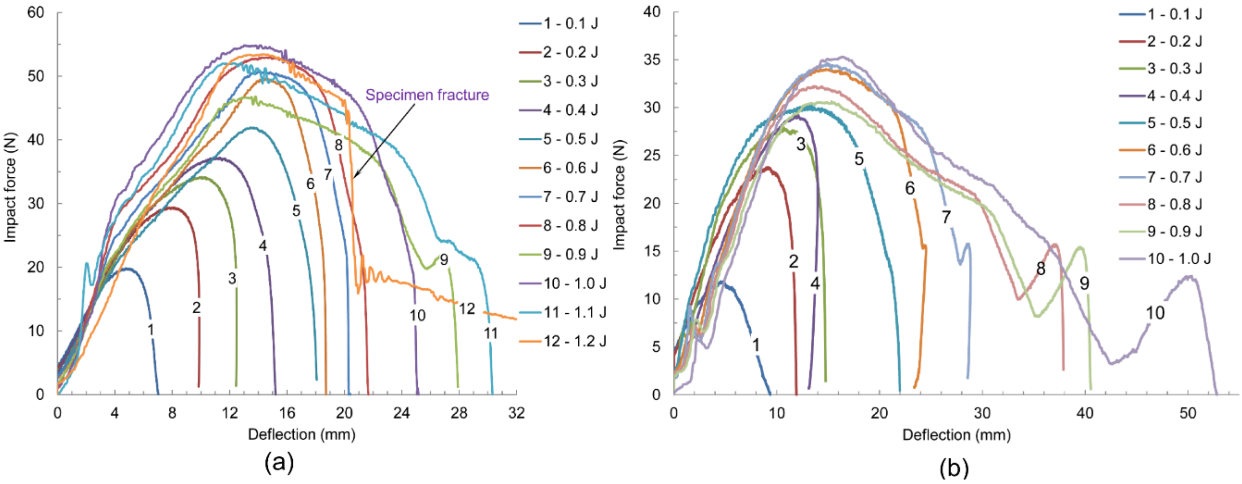

Figure 3. Force-deflection responses of off-axis (a) CFRP and (b) GFRP laminates at various impact energies

The dynamic force-deflection response of off-axis CFRP and GFRP laminates is shown in Fig. 3. As compared to on-axis laminate, both the off-axis laminates showed more yielding-like behaviour at higher energy levels. The CFRP specimens fractured at 1.2 J while the GFRP specimens exhibited permanent set without rupture. The GFRP specimens exhibited large deflection with kinks and slipping of the hammer past the specimen. In the materials under study, apart from the pseudo-ductility in angle ply and GFRP laminates, the TPU matrix was highly ductile material and thus absorbed more energy without inducing any appreciable damage. For the off-axis specimens, only a small increase in stiffness can be observed, at high energy levels. Due to lower stiffness, the maximum deflection of the GFRP specimens was higher than that of the CFRP specimens at the respective impact energy levels resulting in higher strains–to-failure. The off-axis GFRP specimens exhibited pronounced nonlinearity due to viscoplastic fibres apart from matrix plasticity and fibre trellising (pseudo-ductility) in CFRP specimens. The off-axis GFRP also resulted in larger areas under the F-d curves indicating their higher energy absorption capabilities before failure than that of the CFRP specimens. Further, it was also observed that the off-axis laminates required higher impact energies for specified damage and failure than the on-axis specimens.

3. Micro-computed-tomography analysis of damage

Micro computed tomography (micro-CT) was used to analyse the 3D nature of various deformation and damage modes and their location in the impacted on-axis and off-axis CFRP specimens at microstructural level. The CFRP warp and off-axis specimens fractured at 0.6 J and 1.2 J impact energy levels, respectively, were scanned at their fracture (bending) locations.

The tomographs having resolution of 6.1 µm of the on-axis CFRP specimen at the fractured location presented in Fig. 4 demonstrate interply and intraply damage mechanisms at various positions along the sample's width. It is evident that the specimen exhibited progressively matrix cracking and then delaminations and tow debondings until its ultimate fracture. Matrix cracking was dominant in the resin dominated regions surrounding the tows. Interply delamination i.e. separation between adjacent fabric plies and intralaminar delamination such as tow debonding which is separation between tows within a single ply can also be observed. In the fibre-rich regions, the apparent damage mode was debonding at the tow/matrix interface. The analysis of internal structure showed that at the time of fabric fracture which was triggered by tensile fibre failure, almost every ply was delaminated. All the tomographs demonstrate that matrix cracking, delamination and tow debonding and fabric fracture were the significant damage modes at the specimen's bending location.

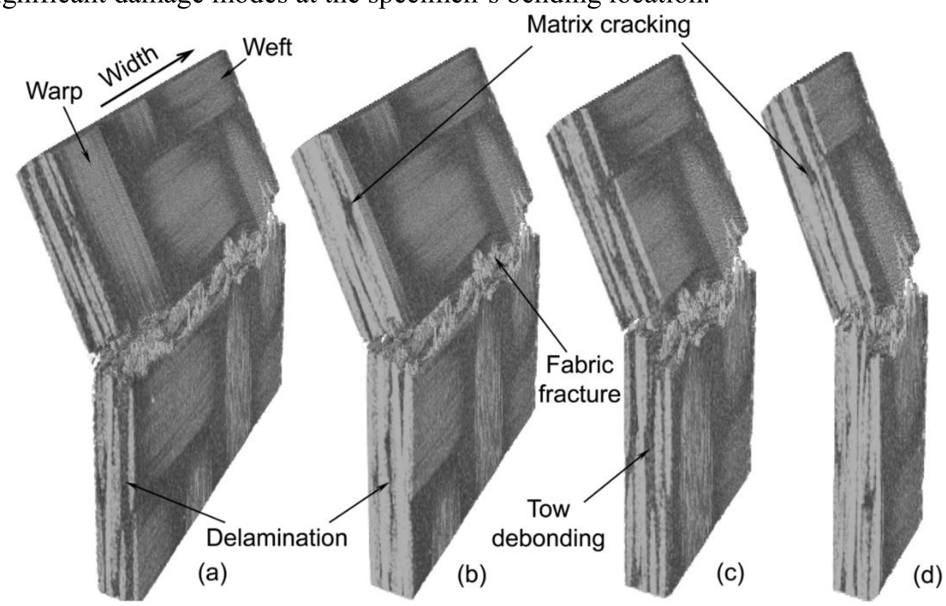

Figure 4. Tomographic 3D images of on-axis CFRP specimen at bending (fracture) location along the height of sample: (a) Full; (b) three-quarter; (c) half; and (d) one-quarter of width

The tomographs of the off-axis CFRP fractured specimen at the bending location are presented in Fig. 5. Here, the samples show similar damage modes of matrix cracking, delamination, debonding and fabric fracture as in the on-axis specimens. However, the extent of damage is less than that occurred in the on-axis specimens. In the off-axis laminates, thicker interply and intraply resin-rich regions are present than in the on-axis ones. In these laminates, the elasto-plastic TPU matrix sharing almost 50% of load with fibres in ±45° orientation was yielded ahead of the crack tip during cracking and delamination; thus enhancing the fracture toughness of woven composites and suppressing damage. In off-axis specimen due to plasticity, the fabric fracture was not as catastrophic as occurred in the on-axis specimens, pierced in two pieces as shown in Fig. 4. Here, the specimen was intact even after the fracture of fabric on its tension side as shown in Fig. 5, thanks to intact tows/fibres on the compression side. Therefore, it is evident that pseudo-ductility in off-axis specimens resulted in damage suppression under dynamic loading.

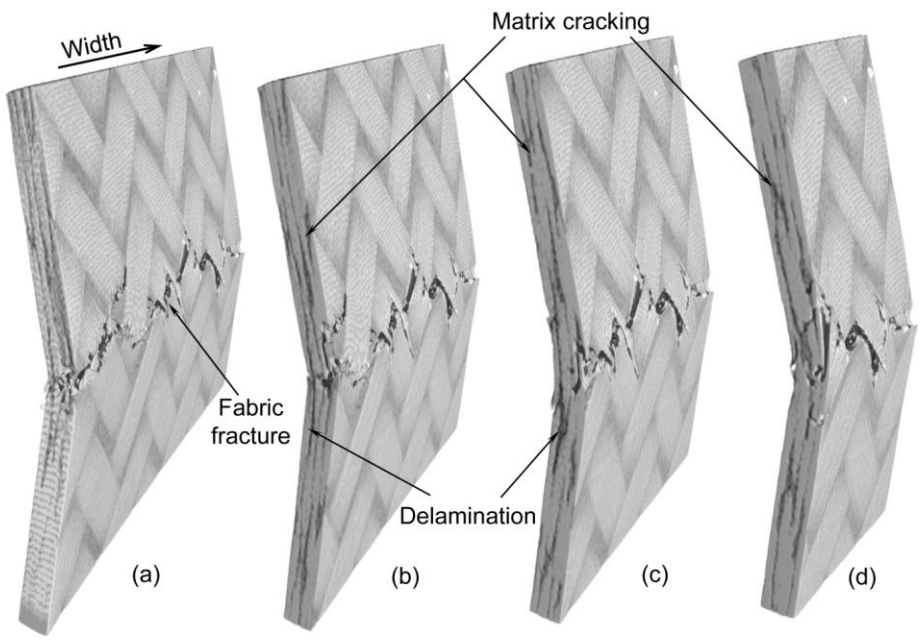

Figure. 5. Tomographic 3D images of off-axis CFRP specimen at bending (fracture) location along the width of sample: a) Full; (b) three-quarter; (c) half; and (d) one-quarter of width

4. Conclusions

In this study, experimental tests were first performed to investigate quasi-static behaviour of CFRP and GFRP laminates in three different configurations of warp, weft and off-axis layups. These tests revealed that the off-axis CFRP and both the on- and off-axis GFRP laminates demonstrated ductile behaviour before their ultimate failure as compared to linear-elastic stress-strain behaviour of the on-axis CFRP laminates. The specimens were then tested under large-deflection dynamic bending at various levels of impact energies up to their ultimate fracture, using the Izod type impactor. The ultimate laminate fracture was characterised by a sudden load drop in the force-deflection plots at the critical energy level of 0.6 J in the on-axis CFRP specimens. This shortcoming of brittle fracture of the on-axis laminates without giving any warning could be alleviated with off-axis as well as glass fabric laminates. The off-axis as well as GFRP specimens exhibited a metals-like ductile behaviour known as pseudo-ductility before their ultimate failure. The off-axis and GFRP specimens sustained impact energy to almost double than that of the on-axis CFRP specimens making them favourable for high-energy absorption. Micro-CT analysis of the tested specimens showed that matrix cracking, delamination, tow debonding and fabric fracture were the dominant damage modes. In the off-axis CFRP laminates, damage evolution was suppressed and delayed by their inherent pseudo-ductility, and the specimen’s failure was not as catastrophic and sudden as in the on-axis CFRP laminates. These characteristics make them suitable for energy-absorption applications with lower safety margins.

References

1. Naik, N., Y. Chandra Sekher, and S. Meduri, Damage in woven-fabric composites subjected to low-velocity impact. *Composites Science and Technology*, 2000. 60(5): p. 731-744.
2. Ullah, H., A.R. Harland, and V.V. Silberschmidt, *Characterisation of mechanical behaviour and damage analysis of 2D woven composites under bending.* Composites Part B 2015. 75 p. 156-166.
3. Ullah, H., A.R. Harland, and V.V. Silberschmidt, Evolution and interaction of damage modes in fabric-reinforced composites under dynamic flexural loading. *Composites Science and Technology*, 2014. 92: p. 55-63.
4. Czél, G., et al., Demonstration of pseudo-ductility in unidirectional discontinuous carbon fibre/epoxy prepreg composites. *Composites Science and Technology*, 2015. 106(0): p. 110-119.
5. Menna, C., et al., Numerical simulation of impact tests on GFRP composite laminates. *International Journal of Impact Engineering*, 2011. 38(8–9): p. 677-685.
6. Pernice, M.F., et al., Experimental study on delamination migration in composite laminates. *Composites Part A: Applied Science and Manufacturing*, 2015. 73: p. 20-34.
7. Ullah, H., A. Harland, and V. Silberschmidt, Experimental and numerical analysis of damage in woven GFRP composites under large-deflection bending. *Applied Composite Materials*, 2012. 19(5): p. 769-783.
8. Bull, D., et al. composite laminate impact damage assessment by high resolution 3D X-ray tomography and laminography. in *18th International Conference on Composite Materials*. 2011. Jeju Island, Korea.
9. Seltzer, R., et al., X-ray microtomography analysis of the damage micromechanisms in 3D woven composites under low-velocity impact. *Composites Part A: Applied Science and Manufacturing*, 2013. 45: p. 49-60.
10. Ullah, H., A.R. Harland, and V.V. Silberschmidt, Damage modelling in woven-fabric CFRP laminates under large-deflection bending. *Computational Materials Science*, 2012. 64: p. 130-135.
11. Fuller, J.D. and M.R. Wisnom, Pseudo-ductility and damage suppression in thin ply CFRP angle-ply laminates. *Composites Part A: Applied Science and Manufacturing*, 2015. 69(0): p. 64-71.
12. Reyes, G. and U. Sharma, Modeling and damage repair of woven thermoplastic composites subjected to low velocity impact. *Composite Structures*, 2010. 92(2): p. 523-531.