Damage and fracture in fabric-reinforced composites under quasi-static and dynamic bending

H Ullah, A R Harland and V V Silberschmidt

Wolfson School of Mechanical and Manufacturing Engineering, Loughborough University, Leicestershire, LE11 3TU, UK

E-mail: V.Silberschmidt@lboro.ac.uk

Abstract. Fabric-reinforced polymer composites used in sports products can be exposed to different in-service conditions such as large deformations caused by quasi-static and dynamic loading. Composite materials subjected to such bending loads can demonstrate various damage modes - matrix cracking, delamination and, ultimately, fabric fracture. Damage evolution in composites affects both their in-service properties and performance that can deteriorate with time. Such behaviour needs adequate means of analysis and investigation, the main approaches being experimental characterisation and non-destructive examination of internal damage in composite laminates. This research deals with a deformation behaviour and damage in carbon fabric-reinforced polymer (CFRP) laminates caused by quasi-static and dynamic bending. Experimental tests were carried out to characterise the behaviour of a CFRP material under large-deflection bending, first in quasi-static and then in dynamic conditions. Izod-type impact bending tests were performed on un-notched specimens of CFRP using a Resil impactor to assess the transient response and energy absorbing capability of the material. X-ray micro computed tomography (micro-CT) was used to analyse various damage modes in the tested specimens. X-ray tomographs revealed that through-thickness matrix cracking, inter-ply and intra-ply delamination such as tow debonding, and fabric fracture were the prominent damage modes both in quasi-static and dynamic test specimens. However, the inter-ply damage was localised at impact location in dynamically tested specimens, whereas in the quasi-static specimens, it spread almost over the entire interface.

1. Introduction

Composite materials have found many applications in aerospace, automotive, medical and construction components and structures due to their better specific strength and stiffness, excellent fatigue strength, good corrosion behaviour and low thermal conductivity. One specific class of composites - woven fabric-reinforced laminates - offer a good resistance to fracture and transverse rupture and high impact strength compared to their unidirectional and cross-ply tape counterparts [1]. These properties have attracted the sports industry to incorporate woven CFRP laminates in the design of sports products. Expanding the application away from the traditional aerospace structures results in
new types of loading regimes such as large-deflection bending experienced in sports products during their service, such regimes were rarely studied. New types of quasi-static and dynamic loads generate high local stresses, leading to complex damage modes, due to heterogeneity and anisotropy of composite laminates. The damage mechanisms typically caused by out-of-plane quasi-static and dynamic bending loads are matrix cracking, fibre breakage and delamination at interfaces within the composite structure [2]. Evolution of these intralaminar and interlaminar damage modes results in significant reduction of in-service mechanical properties and leads to a loss of structural integrity of composite sports products with time [3]. Such internal damage mechanisms, which often cannot be detected by visual inspection, degrade the load-bearing capacity of the structures. Therefore, it is important to study damage suffered by composites under quasi-static and dynamic loading conditions through X-ray micro-computed tomography (micro-CT), which can provide 3D images of internal realisation of deformation mechanisms and their interaction in composites with sufficient resolution, to investigate these internal damage mechanisms. This relatively recent technique has been used to investigate damage mechanisms in composites at micron length scale [4-6]. Therefore, in this study, damage imposed in composites by the new types of loading regimes such as large-deflection quasi-static and dynamic bending experienced by sports products in service is investigated using micro-CT.

The large-deflection behaviour of woven laminates under quasi-static bending have been previously studied by the authors [3, 4, 7, 8]. Most of these studies were based on material characterization using experimental tests and numerical simulations. Similarly, the low velocity impact response of woven-fabric composite laminates has been extensively studied in the literature [9-11]. However, most of the studies were dedicated to the impact behaviour of composites in drop-weight tests, which usually cause localised damage such as penetration and perforation. A large-deflection dynamic bending behaviour of composites caused by a pendulum-type impactor was rarely investigated. Although such an instrumented impactor was used by Silberschmidt et al. [12] and Casas-Rodriguez et al. [13] to study damage in adhesively bonded CFRP joints under repeated impacts, the loading mode was tensile. Recently, the large-deflection dynamic bending behavior of CFRP laminates was studied in [14, 15], using experimental tests and finite-element analyses. One of the latest study conducted by the authors revealed that the damage formation under such dynamic bending conditions was rather different from that observed under drop-weight impact tests [16]. In the present work, which is an extension of the previous studies, formation of various damage mechanisms under quasi-static and dynamic loading regimes is investigated at microstructural level using X-ray micro-CT technique. Quasi-static tests were performed under three-point bending conditions, whereas dynamic tests were carried out using a pendulum type impact tester at various energy levels. The type and location of damage mechanisms in woven CFRP laminates under both types of loadings was identified and compared.

### Table 1. Material properties of twill 2/2 woven CFRP

| $E_{11}$ (GPa) | $E_{22}$ (GPa) | $E_{33}$ (GPa) | $G_{12}$ (GPa) | $G_{13}=G_{23}$ (GPa) | $\nu_{12}$ | Density $\rho$ (kg/m$^3$) |
|----------------|----------------|----------------|----------------|------------------------|-----------|--------------------------|
| 55.0           | 52.0           | 8.0            | 3.8            | 3.0                    | 0.05      | 1470                     |

2. **Experimental methods**

2.1. **Material**

The materials studied were laminates of woven fabric made of carbon fibres reinforcing thermo-plastic polyurethane (TPU) polymer matrix. The material was manufactured from $0^\circ/90^\circ$ prepregs in the form of four plies designated as $[0^\circ,90^\circ]^2$, where $0^\circ$ and $90^\circ$ represent yarns in the warp and weft directions, respectively. The woven laminate had a 2/2 twill balanced weaving pattern; the fabric had the same number of yarns in the warp and weft directions. Quasi-static bending tests were performed at various speeds on rectangular specimens of 80 mm length and 25 mm width with a span-to-
thickness ratio of 40 according to the ASTM D790 standard [17]. Un-notched rectangular specimens of 40 mm length and 25 mm width were prepared for dynamic tests according to the ASTM D4812 standard [18]. The elastic constants of CFRP determined from the quasi-static tests are presented in Table 1; details of the tests for material characterisation are presented elsewhere [7].

2.2. Experimental testing
Quasi-static tests were performed on CFRP specimens at indenter speeds of 100, 200, 300 and 400 mm/min under conditions of three-point large-deflection bending till their ultimate fracture. The flexural stress-strain diagrams of CFRP specimens are shown in Figure 1. Dynamic impact tests were carried out according to the ASTM D4812 standard on an instrumented pendulum type CEAST Resil impactor. In the impact tests, one (lower) part of the specimen was fixed firmly in the machine vice as a cantilever beam. The upper part with a length of 30 mm of the specimen was hit by the striking nose of the pendulum hammer with a controlled level of initial energy, resulting in dynamic large-deflection bending. The distance between the fixed support and the line of contact of the hammer’s striking nose was 22 mm, according to the standard. In this work, a calibrated impact hammer with a mass of 0.6746 kg and a length of 0.3268 m was used. CFRP specimens were tested at energy levels of 0.4 J, 0.5 J and 0.6 J to determine the energy inducing ultimate fracture of the specimens. It was found that the specimen fractured at 0.6 J, corresponding to the initial angle of 64°. Typical records of force vs. time for un-fractured and fractured CFRP specimens are presented in Figure 2.

![Figure 1. Flexural stress-strain response of CFRP laminates in quasi-static tests at various displacement rates](image1)

![Figure 2. Typical force-time response of CFRP laminates in dynamic bending tests at various energy levels](image2)

3. Damage characterisation
Damage such as delamination and matrix cracking usually occurs inside composites laminates and is barely visible. A non-destructive evaluation method, micro computed tomography (micro-CT), was used to visualise the 3D microstructure and internal damage of the tested composite laminates. In this study, micro-CT measurements were performed using an XT H 225 X-ray scanner. The system consists of an X-ray detector and an electronic X-ray source, creating 2D cross-sections of the object. The source is a sealed X-ray tube operating at 25–225 kV with a 3 μm spot size. Following acquisition of tomographic data of the specimen, a software program builds a precise 3D map from 2D radiograph images by 'stacking' the individual slices one on top of the other; this process is known as reconstruction. As denser materials absorb more X-rays than voids and air, this attenuation contrast allows detection and characterisation of cracks and flaws in tomographic images. A small sample with dimensions of 30 mm x 7 mm was prepared from the damaged region of the CFRP specimen tested under quasi-static bending. Additionally, two samples were prepared - one from the fracture region
and another from the impact region of the fractured CFRP laminate tested at 0.6 J in dynamic bending. Dimensions of the fractured and impact samples were 16.4 mm (length) x 8.8 mm (width) and 20.6 mm (length) x 10.2 mm (width), respectively; all the samples had thickness of 1 mm. The data for those samples was collected at 75 kV and 80 μA. Those settings resulted in tomographs with a resolution of 12.7 μm and 14.7 μm for the fractured and impact specimens, respectively.

4. Discussion of results

Results of experimental tests and micro-CT scanning of woven CFRP laminates subjected to quasi-static and dynamic bending are presented in this section. In quasi-static tests as shown in Figure 1, the on-axis specimens exhibited a quasi-brittle response because the applied load was carried by the fibres, which were stronger but brittle than the TPU matrix. Hence, the stress-strain curves were almost linear till ultimate failure, represented by a sudden drop in the stress level. The material also showed strain-rate insensitive behaviour, since carbon fabric-reinforced composites are essentially strain-rate independent in the fibre-dominated modes as elaborated in [16]. The dynamic response of the material at various energy levels is presented in Figure 2. At the energy level of 0.4 J, the loading and unloading parts of the curve have a symmetric parabolic shape suggesting that the respective stages during the contact duration were almost the same, and no significant damage occurred. As the energy level was increased to 0.5 J, the response became unsymmetrical. The oscillations in the load-time response before the peak load represent delamination damage. The impact force at energy of 0.6 J, causing the specimen’s ultimate fracture, is higher. Here, higher impact energy induced larger deformation and therefore, a larger impact force. The load vs. time plot in Figure 2 shows oscillations due to significant damage in the specimen before its ultimate bending fracture. The latter is represented by a sudden drop in the contact force, implying a momentary loss of contact between the impactor and specimen.

![Figure 3](image.png)

Figure 3. Damage mechanisms at various locations across width of CFRP specimen tested under quasi-static bending (resolution 11 μm): (a) edge; (b) 50% of width; (c) 75% of width

Realization of damage mechanisms captured with micro-CT analysis of the CFRP specimen subjected to quasi-static loading is shown in Figure 3, at various locations across the sample’s width. Dark grey regions in the images represent cracks and damage whereas light grey regions represent a higher density material i.e. carbon-fibre yarns. Apparently, before ultimate fracture, the laminate
exhibited matrix cracking, and then delamination in the form of tow debondings. Matrix cracks developed in the weak resin-rich pockets around the tows. Inter-ply and intra-ply delamination (tow debonding) can also be observed. Examination of the internal structure showed that almost every ply was delaminated at the time of fabric fracture. The prominent failure modes were tow debonding, delaminations and, subsequently, transverse ply fracture. The reconstructed 3D images at the bending (fractured) location of the transversely fractured CFRP specimen under dynamic loading are shown in Figure 4. Realisation of damage mechanisms at the outer edge, 50% and 75% of the sample width is shown in Figures 4a, b, and c, respectively. Similarly, tomographs presented in Figure 5 show matrix cracking and delamination at the hammer impact location along the specimen’s height. The X-ray CT images showed that before its ultimate fracture, the laminate exhibited matrix cracking and then delaminations and tow debondings. At the time of fabric fracture, as the analysis of the internal structure revealed, almost every ply was delaminated. All the tomographs showed that matrix cracking

\[ Figure 4. \] Reconstructed 3D images of dynamically tested CFRP specimen at failure location across width of sample (resolution 12.7 µm): (a) edge; (b) 50% of width; and (c) 75% of width

\[ Figure 5. \] Reconstructed 3D images of twill 2/2 CFRP specimen at impact location across height of sample (resolution 14.7 µm): (a) edge; (b) 50% of height; and (c) 75% of height
and inter-ply delamination are the prominent damage modes at the specimen’s impact location, whereas at the bending (fractured) location, these modes are coupled with tow debonding and, subsequently, transverse ply fracture. As evident from Figures 3 and 5, the major modes of damage are the same under quasi-static as well as dynamic loading conditions. However, the interlaminar damage is more localized at the impact region under dynamic loading, whereas in quasi-static loading, these damage modes spread along the length of the specimen.

5. Conclusions
The large-deflection bending behaviour of woven CFRP laminates under quasi-static and dynamic bending was studied using experimental tests and micro-CT scanning. Quasi-static bending tests were carried out to characterise the material’s flexural behavior. Large-deflection dynamic bending tests were performed to investigate the dynamic behaviour and energy absorbing capability of the material. The microstructural analysis was used to observe different damage modes in the impacted specimens with micro-CT, providing a detailed picture of the damage modes and interaction among different failure mechanisms at various locations. It was observed that damage modes such as matrix cracking and delamination were prominent at the impact location, whereas these modes were coupled with tow debonding and fabric fracture at the bending location. Both types of tests resulted in almost similar types of damage mechanisms. However, the spread of damage in specimens subjected to quasi-static loading was more than the localised one in the impact tested samples. The microstructural examination formed a basis for identification of interlaminar and intralaminar damage locations for computational models of woven composite laminates.

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