Damage in woven CFRP laminates subjected to low velocity impacts

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Abstract. Carbon fabric-reinforced polymer (CFRP) composites used in sports products can be exposed to different in-service conditions such as large dynamic bending deformations caused by impact loading. Composite materials subjected to such loads demonstrate various damage modes such as matrix cracking, delamination and, ultimately, fabric fracture. Damage evolution in these materials affects both their in-service properties and performance that can deteriorate with time. These processes need adequate means of analysis and investigation, the major approaches being experimental characterisation and non-destructive examination of internal damage in composite laminates. This research deals with a deformation behaviour and damage in woven composite laminates due to low-velocity dynamic out-of-plane bending. Experimental tests are carried out to characterise the behaviour of such laminates under large-deflection dynamic bending in un-notched specimens in Izod tests using a Resil Impactor. A series of low-velocity impact tests is carried out at various levels of impact energy to assess the energy absorbed and force-time response of CFRP laminates. X-ray micro computed tomography (micro-CT) is used to investigate material damage modes in the impacted specimens. X-ray tomographs revealed that through-thickness matrix cracking, inter-ply delamination and intra-ply delamination, such as tow debonding and fabric fracture, were the prominent damage modes.

1. Introduction

Woven-fabric reinforced composites offer 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, which could be subjected to large-deflection bending and multiple impacts in service. Such types of dynamic loads can generate high local stresses, leading to complex damage modes, due to the heterogeneity and anisotropy of composite laminates. The damage mechanisms typically caused by out-of-plane impact loads are matrix cracking, fibre breakage and delamination at interfaces within the composite structure [2]. Impact damage and, in particular, delamination occurring at low velocity impact cause a significant decrease in the material’s in-plane compressive strength and stiffness. 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 the damage suffered by the composites under impact loading conditions.

The low velocity impact response of woven-fabric composite laminates has been extensively studied in the literature [3-5]. However, the majority of the studies are dedicated to the impact behaviour of composites studied in drop-weight tests, which usually cause localised damage such as
penetration and perforation. Large-deflection dynamic bending behaviour of laminate composites caused by a pendulum-type impactor is rarely investigated. Although such an instrumented impactor was used by Silberschmidt et al. [6] and Casas-Rodriguez et al. [7] to study damage in adhesively bonded CFRP joints under repeated impacts, the loading mode was tensile. The authors have previously studied large-deflection behaviour of woven laminates under quasi-static bending [8-11]. In the present work, a large-deflection bending behaviour of woven-fabric CFRP laminates subjected to impact loads is studied. Flexural impact tests were carried out using a pendulum type impact tester at various energy levels. The type and location of damage was investigated with X-ray micro-CT.

![Two-dimensional image of CFRP 2/2 twill weave](image1)

**Figure 1.** Two-dimensional image of CFRP 2/2 twill weave

![Resil impact test set-up](image2)

**Figure 2.** Resil impact test set-up

2. Experimental

2.1 Material

The materials studied were laminates of woven fabric made of carbon fibres reinforcing a thermoplastic polyurethane (TPU) polymer matrix. The material was manufactured from 0°/90° prepregs in the form of four plies designated as $[0°,90°]_2s$, where 0° and 90° represent yarns in the warp and weft directions, respectively. The woven laminate had a 2/2 twill balanced weaving pattern shown in Figure 1; the fabric had the same number of yarns in the warp and weft directions. Un-notched rectangular specimens of 40 mm length and 25 mm width were prepared according to the ASTM D4812 standard [12]. The parameters of the 2/2 twill weave fabric composite are listed in Table 1.

**Table 1.** Parameters of CFRP twill 2/2 woven composite

| Parameter                        | Value                  |
|----------------------------------|------------------------|
| Fibre type                       | Carbon T200            |
| Yarn filament count              | 3000                   |
| End/pick count, yarns/cm         | 5.2/5.14               |
| Fabric areal density (g/m²)      | 200                    |
| Polymer                          | Thermoplastic polyurethane (TPU) |
| Laminate density (g/cm³)         | 1.47                   |
| Fibre volume fraction (%)        | 45                     |
| Number of layers                 | 4                      |
| Laminate thickness (mm)          | 1.0                    |
2.2 Impact testing

Dynamic impact tests were carried out according to the ASTM D4812 standard on an instrumented pendulum type CEAST Resil impactor as shown in Figure 2. In the impact tests, the bottom of the specimen was fixed firmly in the machine vice as a cantilever beam. The upper 30 mm of the specimen was struck 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. The hammer can generate maximum impact energy of 2 J at an impact velocity of 3.46 m/s, corresponding to an initial angle of 150° to the striking position. The magnitude of initial impact energy and velocity can be varied by changing the initial angle of the hammer. Increasing the initial angle of the hammer results in an increased impact energy and thus higher peak loads as can be seen in Figure 3 for 0.5 J and 0.6 J impacts corresponding to 58° and 64° angles. A piezoelectric force transducer was fixed rigidly to the hammer striking nose to capture the impact force signal. When the pendulum hammer is released from the pre-defined initial angle, the impact with the specimen generates a change in electrical resistance of the piezoelectric sensor that is captured by the data acquisition system (DAS 8000) connected to the Resil impactor. The signal is registered with a pre-defined sampling frequency of 833 kHz, with up to 8000 data points recorded per impact test. In order to decrease the data noise, a 1 kHz filter was used. CFRP specimens were tested at various energy levels to determine the energy inducing ultimate fracture of the specimen. Two samples per energy level were subjected to single impact loading. It was found that the specimen fractured at 0.6 J, corresponding to an initial angle of 64°. The rest of the tests were carried out at 0.5 J (corresponding to 58°) to study the behaviour of sub-critical damage modes such as matrix cracking and delamination. Typical records of force vs. time for un-fractured and fractured CFRP specimens are presented in Figure 3. Similarly, evolution of the specimen absorbed energy is shown in Figure 4.

![Figure 3. Typical force-time response of 2/2 twill woven CFRP laminate in impact tests](image)

![Figure 4. Typical absorbed energy-time response of 2/2 twill woven CFRP laminate in impact tests](image)

3. X-ray micro computed tomography (micro-CT) for damage characterisation

Damage such as delamination and matrix cracking usually occurs inside composites laminates and is barely visible. The damage mechanisms need examination for reliable and accurate analysis of the behaviour and performance of composite laminates. 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. This technique has been used to investigate micro cracking and delamination in woven composite laminates at micron-range scale [13]. In this study, X-ray 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. The specimen was positioned in a set
up allowing two translations and one rotation, rotating and raising/lowering the sample to a specific region of interest for adjustment of the sample magnification and acquisition of tomographic data. Following acquisition, 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 high scan resolution is required to obtain the required internal details of damage in a composite laminate; as the resolution is increased, the field of view of the sample is reduced. However, samples must remain within the field of view to obtain the radiographs of the region of interest, thus there is a trade-off. Two samples, one from the fractured region and another from the impact region of the fractured CFRP laminate tested at 0.6 J were prepared to meet these requirements. Sizes of the fractured and impact samples were 16.4 mm length x 8.8 mm width x 1 mm thickness and 20.6 mm length x 10.2 mm width x 1 mm thickness, respectively. The data for those samples was collected at 75 kV and 80 μA. Transmission X-ray images were acquired from 3600 rotation views over 360° of rotation (0.1° rotation step) for 3D reconstruction. Those settings resulted in tomographs with a resolution of 12.7 μm and 14.7 μm for the fractured and impact specimens, respectively.

![Figure 5](image1.png)

**Figure 5.** Reconstructed 3D images of a 2/2 twill CFRP specimen at the failure location across the width of the sample (resolution 12.7 μm): (a) edge; (b) 50% of width; and (c) 75% of width

4. Discussion of results

Results of experimental tests and micro-CT scanning of woven CFRP laminates subjected to low velocity impacts are presented in this section. Specimens were subjected to impact energies of 0.5 J and 0.6 J using an instrumented pendulum impact hammer. Figure 3 shows the variation of load with time for both energy levels. At the energy level of 0.5 J, the loading and unloading curve has a symmetrical parabolic shape suggesting that the respective stages during the contact duration are almost the same, and no significant damage occurred. Although the un-fractured samples underwent interlaminar damage before the structure lost its load-carrying capacity, the development of such inter-ply delamination was not reflected in the force-time plot for 0.5 J in Figure 3. The impact force at 0.6 J energy, causing the specimen’s ultimate fracture, is higher. Here, a higher impact energy induces larger deformation and therefore, larger impact force. The load vs. time graph in Figure 3 shows oscillations due to significant damage in the specimen before its ultimate bending fracture. The ultimate fabric fracture is represented by a sudden drop in contact force, implying a momentary loss of
contact between the impactor and specimen. Figure 4 shows the variation of the specimen’s absorbed energy with time. The amount of energy transferred from the impactor to the composite specimen at the end of impact events, i.e. absorbed energy, increases with the impact energy since a higher impact energy results in a more severe damage to the composite specimen. As shown in Figure 2, the absorbed energy increases with time during loading, reaches a maximum value and then decreases during unloading, and finally remains horizontal, i.e. reaches a constant value for 0.5 J impact energy. For 0.6 J impact energy, the absorbed energy reaches a value of 0.48 J at 6 ms and then gradually increases. The stabilized energy level indicates that the impactor has lost contact with the specimen. This constant value gives the total energy absorbed permanently by the composite specimens at the end of an impact event.

Figure 6. Reconstructed 3D images of twill 2/2 CFRP specimen at impact location across the height of sample (resolution 14.7 µm): (a) edge; (b) 50% of height; and (c) 75% of height

The reconstructed 3D images of the transversely fractured CFRP specimen at the bending (fractured) location are shown in Figure 5. Realisation of inter-ply and intra-ply damage mechanisms at the outer edge, 50% and 75% of the sample width is shown in Figure 5a, 5b, and 5c, respectively. Similarly, tomographs presented in Figure 6 shows matrix cracking and delamination at the hammer impact location along the specimen height. Dark grey regions in the images represent cracks and damage whereas light grey regions represent higher density material i.e. carbon-fibre yarns. The X-ray CT images have shown, before its ultimate fracture, the laminate exhibited matrix cracking and then delaminations and tow debondings. Matrix cracks developed in the weak resin-rich pockets around the tows. Inter-ply delamination and intra-ply delamination such as tow debonding can also be observed. Such delaminations normally appeared near the matrix cracks areas, which suggest that formation of the cracks initiated delamination. In the fibre-rich regions the damage was associated with debonding at the fibre/matrix interface. At the time of fabric fracture, as the analysis of the internal structure has showed, almost every ply was delaminated. All the tomographs showed that matrix cracking 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.

5. Conclusions
The large-deflection bending behaviour of woven CFRP laminates under low velocity impacts was studied using experimental tests and micro-CT scanning. Impact tests were carried out to characterise the material’s dynamic behaviour and impact strength. Experimental results highlighted the energy absorbing capabilities of the CFRP composites. The micro-structural analysis was performed to observe different damage modes in the impacted specimens using 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. The micro-structural examination has formed a basis for identification of interlaminar and intralaminar damage locations for future computational models. Further, the dynamic testing results will define the design load envelope for various sports products subjected to large-deflection dynamic bending.

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