SYNCHROTRON COMPUTED TOMOGRAPHY OF FATIGUE MICROMECHANISMS IN CFRP

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1 Introduction

Carbon fibre reinforced polymers (CFRPs) have developed into a core lightweight structural technology, underpinning major engineering applications, primarily in aerospace [1]. Fatigue design methodologies for composite laminates are not well established: life prediction is complicated by multiple damage modes, including fibre/matrix debonding, matrix cracking, delamination, and fibre breaks [2,3]. Damage behaviour and interacting mechanisms have been extensively investigated, using different approaches, resulting in various modeling strategies for predicting fatigue life [e.g. 4-16]. However, these activities have not hitherto identified distinctly the mechanisms responsible for fatigue damage initiation, and subsequent growth or those, which result in ultimate failure and determine fatigue life, based on physical observations. This lack of understanding is complicated by the inability to directly inspect critical internal damage processes using optical and/or electron microscopy. Improvements on this situation have been achieved recently by the availability of high resolution computed tomography, which allows the imaging of damage down to the scale of individual broken fibres [17]. Various non-destructive techniques have been employed to detect fatigue damage in composites; ultrasونics to evaluate delamination [18-20], acoustic emission to monitor the formation and growth of damage [21-24], and thermography to correlate damage and strain [25,26]. These methods have their individual intrinsic limitations, such as the inability to provide direct information on type, size and orientation of damage, to resolve fine-scale (fibre/matrix debonding and fibre breaks), and to provide a three-dimensional representation of damage. X-ray Computed Tomography (CT) is now established as a powerful technique for contemporary material science studies, allowing multiscale analysis (macro, micro, meso and nano) of structure and behaviour to be performed [27-32]. It has been demonstrated that a voxel resolution in the order of one micrometre is reasonable to detect and distinguish primary damage modes in composites [33].

In the case of fibre-reinforced polymers, X-ray CT has been used to evaluate the local volume fraction and orientation of reinforcement [34], voids and internal damage in glass/epoxy [35,36], and fibre fracture of quartz/epoxy bundles [37]. Damage of CFRPs under impact and quasi-static loading has been assessed in previous work using Synchrotron Radiation Computed Tomography (SRCT) imaging, evidencing multiscale interacting 3D failure processes [38-40]. However, to the best of the authors’ knowledge, there are no high resolution CT investigations on fatigue behaviour for composite materials.

In this work, in situ SRCT imaging has been exploited in carbon/epoxy cross ply laminates to characterize micromechanical fatigue behaviour and to quantify damage. Comparison with the results of a previous study conducted by Moffat et al. [41] on damage growth in quasi-static loading of the same material system has been carried out.

2 Materials and methods

M21/T700 carbon/epoxy prepreg (nominal volume fraction of fibre 60%), with a [90/0], layup, was investigated. The material was laid up and autoclave cured using a standard aerospace cure cycle as specified by the material supplier. Double-edge notched specimens, with a gauge length of 66 mm and width of 4 mm, were prepared from the laminated plates, using waterjet cutting. Two semi-
circular notches, of radius 1 mm were introduced during the water jet cutting, leaving a nominal net section between the notches of 2 mm. Aluminum tabs were attached to facilitate loading, as reported by Wright et al. [40], Fig. 1. The average ultimate tensile failure stress ($\sigma_f$) was previously evaluated, reporting a value of 960 MPa across the net section [40]. Tensile fatigue tests, with sinusoidal waveforms and load ratio of R=0.1, were performed using two load levels, corresponding to 30% and 50% of $\sigma_f$ respectively at a frequency of 10 Hz, and up to $10^6$ load cycles. Fatigue cycling was carried out using a servo-hydraulic load frame equipped with hydraulic grips. After fatigue load was applied, specimens were scanned at the Swiss Light Source using synchrotron X-ray radiation. In situ loading experiments were performed on the TOMCAT-X02DA Beamline, Paul Scherrer Institut, Villigen, Switzerland. The distance between specimen and detector was set to 30 mm, providing a degree of phase contrast (edge detection regime). The beam energy was 19 KeV (multilayer, bandwidth of the order of a few percent). Specimens were placed in the load frame on the rotating stage, and two load sequences were recorded, corresponding to the unloaded and loaded state respectively. During each tomographic scan, 1500 projections were collected on a 2048 x 2048 pixels detector, through a rotation of 180˚. The exposure time for each radiograph was 150 ms, resulting in a scan time of approximately 4 minutes.

An isotropic voxel resolution of 1.5 µm was achieved, a value, which is considered reasonable to inspect damage at the level of individual fibres and toughening particles.

Two scans were conducted for each specimen and load level in order to extend the field of view along the sample length to capture all of the damage. Three-dimensional reconstruction was obtained from radiographs using an in-house code based on the GRIDREC/FFT approach [42]. Fatigue damage was studied using the commercial software VG studio Max v2.1. Initially reconstructed volumes were analyzed by inspecting orthogonal 2D slices. Bright fringes around the cracks (see Fig. 2b) resulting from phase contrast were exploited to identify cracks, particularly where these were narrow.

![Fig.2. Three dimensional rendering of fatigue damage modes (a), slide perpendicular to the loading direction within the notch zone (b).](image-url)
Defining a region of interest around the damage and applying a semi-automated segmentation technique, based on the seed-growing algorithm [33], damage was segmented, as shown in Fig. 2a, where the bulk composite material has been set as semi-transparent and the crack volumes coloured by type. Segmented crack volumes were separately extracted and quantified in terms of crack length, crack opening displacement (COD), and crack shear displacement (CSD). Specifically, ImageJ was employed to binarize the crack volume by the Max Entropy threshold method [43]. Data obtained has been processed using Matlab routines to describe the crack profile shape; the average split length, the COD corresponding to the root and to the tip of the splits.

3 Results and discussion

3.1 Fatigue damage

Segmentation allowed three-dimensional fatigue damage to be characterized, providing the identification of the different damage types, their location and shape. Observations have shown the presence of intralaminar and interlaminar damage at both high and low load levels. Fig. 3 illustrates intralaminar damage, consisting of transverse ply cracks and splits. Transverse ply cracks initiate in the 90˚ ply around the notch, develop from one side to the opposite across the ply thickness, and increase in number with the increasing load. In the 50% $\sigma_f$ loading case some transverse ply cracks do not completely propagated across the ply thickness, initiating from the specimen edges.

Splits originate from the notch and propagate parallel to the load direction within the 0˚ ply. Increasing load level resulted in an increase in split length, which exceeded the field of view for the 50% $\sigma_f$ load state, Fig. 3b. Splits do not advance evenly, see Fig. 3a, being affected by the presence of resin rich regions which contain the majority of toughening particles. Isolated fibre breaks were observed along the splits, most of them associated with fibres misaligned with respect to the loading direction.

![Fig.3. Three dimensional intralaminar fatigue damage for 30% $\sigma_f$ (a) and 50% $\sigma_f$ (b).](image-url)

![Fig.4. Damage modes interaction at the interface with confluence of 0˚ splits, delamination and transverse ply cracks; CT slide in the xy plane (a), and 3D segmentation of the damage types (b).](image-url)
Delamination has been detected at the ply interfaces; these represent zones of particular interest due to the damage interaction with toughening particles, Fig. 4.

3.2 Micromechanical characterization

It has been observed that damage propagation depends on the microstructure, which determines the crack path development across the ply thickness. A 0° split, obtained by loading to 30% $\sigma_f$, is shown in three orthogonal cross-sections, in Fig. 5. Section 5a shows split occurring within a resin-rich region. Debonded toughening particles are clearly visible, which with their spacing determine the distance between echelon cracks oriented at approximately 45° with respect to the loading direction.

Section 5b shows typical behaviour in a region with a higher local fibre volume fraction. Damage is more constrained compared with the resin rich regions, and as a consequence the crack surface is closely aligned with the loading direction. Section 5c depicts split growth in a large resin rich region. The micromechanical behaviour appears slightly different compared with the section shown in 5a, due to the presence of microcracks along the path split, which cut through toughening particles. Similar behaviour has been also detected for a load of 50% $\sigma_f$. Transverse ply cracks developed across the 90° ply thickness. Fig. 6 shows a transverse ply crack section near the interface with the neighbouring 0° ply.

![Fig. 6. Transverse ply crack near the interface for 30% $\sigma_f$ fatigue load.](image)

Toughening particles have partially debonded and contribute to bridging ligaments across the crack. Misaligned fibres have also been detected across the transverse ply cracks; some of these act as bridging ligaments between the crack flanks; others are broken.

3.3 Damage quantification

Damage quantification has been conducted focusing on the evaluation crack length and crack opening displacement of splits using COD greyscale maps as shown in Fig. 7. This follows earlier work [40,41] on splits propagated under quasi-static loading. Splits are not planar; however, the COD map represents a 2D projection of the split onto the plane of the 0° plies, obtained by summing the voxels in the through-thickness direction. Fig. 7a and Fig. 7c show the crack opening contour map of splits grown in fatigue loading at 30% and 50% $\sigma_f$ respectively. Dark regions correspond to large values of COD, while white regions are uncracked. Fig. 7b and Fig. 7d show corresponding transverse cross-sections of splits taken at 140 µm from the notch mid-plane. The COD greyscale maps in Fig. 7a and Fig. 7c show that the crack front advances further in regions with higher local fibre volume fractions. In resin-rich regions toughening particles, interact with the damage, appearing to retard crack growth. This behaviour explains the very visible bands across the split shown in Fig. 7a. Close to the interfaces with the 90° plies, i.e. from 0 µm to 80 µm and from 400
μm to 450 μm, the less open, more retarded crack corresponds to resin rich regions near the interfaces. Another less open, more retarded resin rich region is located in the middle of the 0° ply, 180 - 280 μm, within which the echelon cracks are clearly visible along the split length.

Between these resin rich regions, two high fibre volume fraction zones are present, from 80 μm to 180 μm and from 280 μm to 400 μm, characterized by higher local crack opening and a jagged crack front.

The COD map for an applied load of 50% σf was obtained by concatenating images from two adjacent segmented volumes, as shown in Fig. 7c. Similar behaviour to the lower load is observed; two resin rich zones within the split, from 60 μm to 100 μm and from 360 μm to 400 μm, interspersed with higher fibre volume fraction regions. However, at 50% σf the damage propagation appears to be more homogeneous (crack extension is less locally pinned), with reduced bridging in the resin rich regions, particularly at the interfaces with the 90° plies. The change in crack front shape is in the first instance attributable to the increased delamination seen at the higher load level, which is expected to reduce the constraint on opening from the 90° ply.

Considering regions of interest at the tip and at the root of the split via the COD map, average values of COD have been evaluated. Results indicated values of COD decreasing towards the crack tip. Fig. 8 displays this typical trend, obtained considering a region of interest that extends from root to tip of the split at 30% σf.

Crack shear displacement (CSD) associated with the 0° split has been evaluated following the methodology of Toda et al. [44] using the occasional

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Fig.7. Crack opening displacement contours of splits for 30% (a) and 50% σf (c) fatigue load; corresponding CT cross-sections along the ply thickness at a distance of 140 μm from the notch mid-plane (b), (d).

Fig.8. Average crack opening displacement along the split at 30% σf fatigue loading.

Fig.9. Crack shear displacement evaluation: fibre breaks as reference features (a), and (b) schematic representation of the shear strains that develop in correspondence of 0° split.
fibre breaks along splits as reference features, as shown in Fig. 9. Measuring the displacement, along the fibre direction, between the two sections of the considered fibre breaks, CSD was obtained. Results indicated the dependence of CSD on the position along the split, decreasing with the distance from the notch. For 30% and 50% $\sigma_f$ at a distance of 450-550 $\mu$m from the notch mid-plane was found CSD of 8.86 $\mu$m ($\pm$ 1.5 $\mu$m) and 16.21 $\mu$m ($\pm$ 1.5 $\mu$m) respectively.

3.4 Fatigue and quasi-static damage comparison

Qualitative analysis using 3D rendering of damage has demonstrated broadly similar behaviour between fatigue and quasi-static loading in term of crack location and shape. However, fatigue results in more extensive damage than quasi-static at the same peak load. In addition, delamination is not detected for these loads of quasi-static load whereas quite extensive delamination is observed in fatigue. In both quasi-static and fatigue a strong correlation between damage and microstructure was observed, suggesting a similar behaviour of split propagation in resin rich regions and high-fibre volume fraction regions.

Fig. 10 displays a cross section of a split in a resin rich-region for quasi-static loading (Fig. 10a), and for fatigue (Fig. 10b); both cases loaded at 50% $\sigma_f$.

The echelon cracks are much more apparent in the quasi-static loading case, as shown in, Fig. 10a. In cyclic loading the bridges between the individual cracks appear to have largely failed, presumably due to fatigue, resulting in more continuous cracks as shown in, Fig. 10b.

Similar behaviour is also demonstrated in comparisons of transverse ply cracks near the 0° ply interfaces, as shown in Fig. 6 (fatigue) and Fig. 11 (Q-static). In fatigue the crack is more continuous with less bridging ligaments than observed in Q-static loading. COD greyscale maps for quasi-static load have been evaluated by Moffat et al. [41] and are reproduced in this work to allow a quantitative comparison.

Fig. 10. Comparison of micromechanical behaviour between quasi-static (a) [41], and fatigue (b).

Fig. 11. Transverse ply crack near the interface induced by quasi-static load [41].

Fig. 12. Split crack opening displacement contours at 40% $\sigma_f$ (a) and 50% $\sigma_f$ (c) for Q-static loading [41]; corresponding CT cross-sections along the ply thickness at 140 $\mu$m from the notch mid-plane (b), (d).

Fig. 12 represents a COD map in Q-static loading for equivalent peak loads to that used in fatigue. Split sections in the transverse plane are compared at
the same distance from the notch mid-plane as in the fatigue case. Direct comparisons can be made between the quasi-static (Fig. 12) and fatigue loading case (Fig. 7). The general features are similar between quasi-static and fatigue; however, the crack pinning in resin-rich regions containing toughening particles is clearly more effective in quasi-static loading. After fatigue loading the crack opening is more homogeneous across the split width, with less pronounced crack bridging in the resin rich regions. The crack front is also much less jagged, both in absolute terms and also when expressed as a fraction of the average crack length. Average COD values found by Moffat et al. [41], albeit on shorter splits, for quasi-static load correspond to 1-3 µm and 3-6 µm for 40% and 50% σf respectively. As shown in Fig. 7 and Fig. 12 fatigue splits are characterized by higher values of COD compared to quasi-static loading. This behaviour is consistent with fatigue degradation of the toughening mechanisms associated with the toughening particles. Similarly fatigue demonstrated a crack shear displacement of 16.21 µm (± 1.5 µm) at 50% σf, whereas for quasi-static a value of 8.4 µm (± 1 µm) was estimated for the same distance from the notch mid-plane [41].

4 Conclusions

SRCT has been demonstrated as an effective non-destructive technique providing novel image analysis of fatigue. Similarities and differences at the micromechanical level between fatigue and quasi-static have been identified quantitatively. Interaction between damage and microstructure are seen to be broadly similarly, but with significant differences in terms of the incidence and extent of crack bridging and delamination that lead to an apparently reduced effect of toughening particles in fatigue.

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References


[34] G. Requena, G. Fiedler, B. Seiser, P. Degischer, M. Di Michiel and T. Buslaps “3D-Quantification of the distribution of continuous fibres in unidirectionally...


