IN SITU FIBRE FAILURE MAPPING ON CFRP BY ULTRAFAST COMPUTED TOMOGRAPHY

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Keywords: Carbon/epoxy, Quasi-static load, Fibre failure, Ultrafast X-ray computed tomography

Abstract
In situ ultrafast synchrotron X-ray computed tomography was used to investigate fibre failure micromechanisms in a toughened particle carbon/epoxy (M21/T700) under quasi-static load. The methodology proposed enables to monitor fibre breaks nucleation and accumulation unambiguously in real time (4D), thus avoiding application of prolonged load times and reducing exposure to radiation compared to step-by-step scans. This study for the first time provides an overview of the damage detected till one second before failure for a double-notch coupon. Results show the progression of single breaks and clusters, their location with respect to the pre-existing failed fibres and respect to the other damage modes. Multiple breaks were also detected on a single fibre, allowing to identify the sequence of fragmentation for incremental loads.

1. Introduction

Fibre failure is known to be the critical damage mechanism in tension, where the axial strength of unidirectional composites is controlled by the strength distribution of fibres. Several models were developed to predict fibre-dominated tensile strength [1-5]. However, there are still unknown or not well-understood aspects related to the physical mechanisms behind fibre failure, essential to inform and validate accurate predictive models. This is particularly relevant for mechanisms occurring just before the final failure [5,6], as they cannot be observed with traditional techniques. Previous work has successfully exploited *in situ* SRCT imaging of CFRPs under quasi-static load [7, 8] and fatigue [9], evidencing multiple interacting 3D failure processes and providing successfully novel quantitative analyses to inform numerical models [8,10].
Accumulation of fibres failure under tensile loads was assessed by *in situ* interrupted tensile experiments in previous work [7] revealing a drastic increase in fibre breaks when approaching the ultimate tensile stress. However, the main limitation associated with the use of single static scans is represented by the inability to capture instable mechanisms preceding failure. Ultrafast computed tomography was used in this study to assess the real time nucleation and accumulation of fibre breaks till one second before the final failure.

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2. Methodology

2.1 Material

The material system used in this study is a thermoplastic particle toughened carbon/epoxy (M21/T700) with a nominal volume fraction of fibre of 60% and a $[90/0]_s$ layup [11]. Double-edge notch specimens, with a nominal central cross-section of 1 mm and a length of 66 mm were cut by waterjet from a composite plate with a thickness of 1 mm. Aluminum T-tabs were glued to allow the application of tensile load using the *in situ* loading rig, and to guarantee alignment of the specimen during the test. Details on the geometry and dimensions of the coupons are reported in Figure 1. The average ultimate tensile stress (UTS) equal to 960 MPa was evaluated elsewhere [8]. However, in this experiment the coupon failed for a considerably higher load, corresponding to the UTS of 1400 MPa.

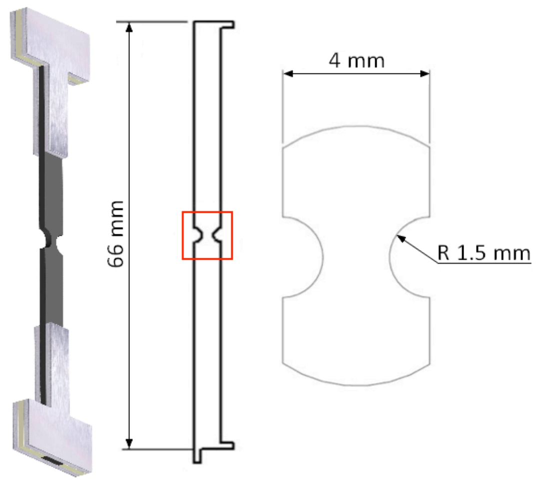

Figure 1. Coupon geometry and dimensions used.

2.2 Experimental procedure

The specimen was placed in the loading rig and scanned in the undamaged and unloaded condition with the aim to assess the initial condition, such as presence of manufacturing defects or damage related with the specimen cutting and preparation. After this initial scan, the coupon was loaded and scanned continuously till failure. Single fast scans at an intermediate percentage of the UTS (55% and 85% UTS) were performed, while 11 scans were carried out in the last 11 seconds before failure. Based on the objective of this study, data acquired in these last 11 seconds before failure were analysed and presented.
Tensile tests were performed using the tension-compression INSA-Lyon rig [12]. The region of interest for the scans was located around the notch (see Figure 2(a)), where the final failure occurred. *In situ* experiments were performed at the Swiss Light Source (on the TOMCAT-X02DA Beamline, Paul Scherrer Institut, Switzerland). The beam energy was 20 keV and the distance between specimen and detector was set to provide a degree of phase contrast. The exposure time was 2 ms and the number of projection 500, thus resulting in 1 scan per second. The voxel resolution chosen was 1.1 μm that corresponds with to a field of view of ~ 2.2 x 2.2 mm^2. Reconstructions were obtained using an in-house code based on the GRIDREC/FFT approach [13]. Reconstructed volumes were registered using ImageJ in order to facilitate the correlation through the different scans. A median filter was applied to the original data to reduce noise. Fibre breaks were visually inspected with VGStudio MAX v2.1 and Avizo 9 by the use of all the orthogonal views to avoid any uncertainty.

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3. Results

3.1. Evolution of damage modes in the notch region

Damage modes evolution in the notch region was evaluated in order to assess potential correlations with the nucleation and accumulation of fibre breaks. The three-dimensional rendering of the scanned region of interest is shown in Figure 2(a) for the scan obtained 1 second before failure. The damage modes detected are:

- Transverse ply cracks with an average crack opening on the order of 200 µm. These are located in the 90 plies symmetrically respect to the notch geometry, see Figure 2(a) and Figure 2(b). Bundle of fibre bridging the two flanks were observed; see Figure 2(a).
- Transverse ply cracks with an average opening of 20 µm.
- 0º ply splits originated from the notch.
- Delamination occurring at the interconnection between transverse ply cracks and 0º ply splits.
- Fibre breaks located in the 0 plies within the region delimitated by the 0º ply splits and delamination.

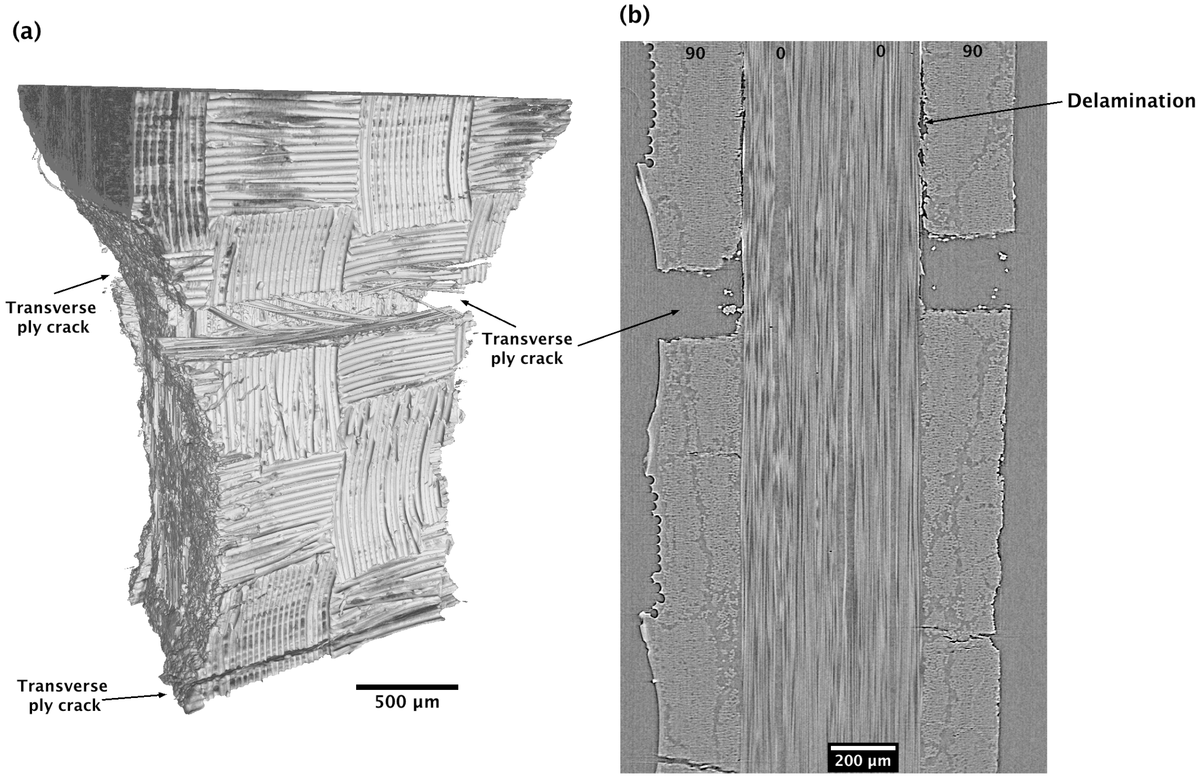

Figure 2. 3D rendering of the notch region scanned (a), a cross-section parallel to the loading direction (b).

3.2. Fibre breaks accumulation

The number of additional breaks in the last 11 seconds was 41 out of 581 quantified for the whole duration of the test. Most of the fibres appeared as singlets (single breaks) or 2-plets (two adjacent fibre breaks), as summarised in Table 1. The largest cluster detected in the last 11 seconds was of 5-plet (see Figure 3), while the largest cluster observed during the whole load history was of 10-plet, already present during the first dynamic scan.

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Table 1. Number and type of fibre breaks detected in the 0 plies at 11 seconds (volume 1) and 1 second (volume 11) before failure of the coupon.

	Volume 1	Volume 11
Singlet	322	339
2-plet	51	56
3-plet	14	17
4-plet	6	6
5-plet	4	5
6-plet	1	1
7-plet	2	2
10-plet	1	1
TOT	**540**	**581**

Fibre accumulation was not associated with the growth of pre-existing failed fibres, but the additional breaks detected were ‘new born’ in correspondence of new locations, both single and multiple breaks. Figure 3 shows an example where the same cross-section parallel to the loading direction is taken into account across the dynamic sequence of scans. Initially, no fibre breaks are observed in Figure 3(a), while 5 breaks appear within the temporal resolution (1 second) as a multiple co-planar break (Figure 3(b)). Such cluster did not show any evolution till failure, Figure 3(c).

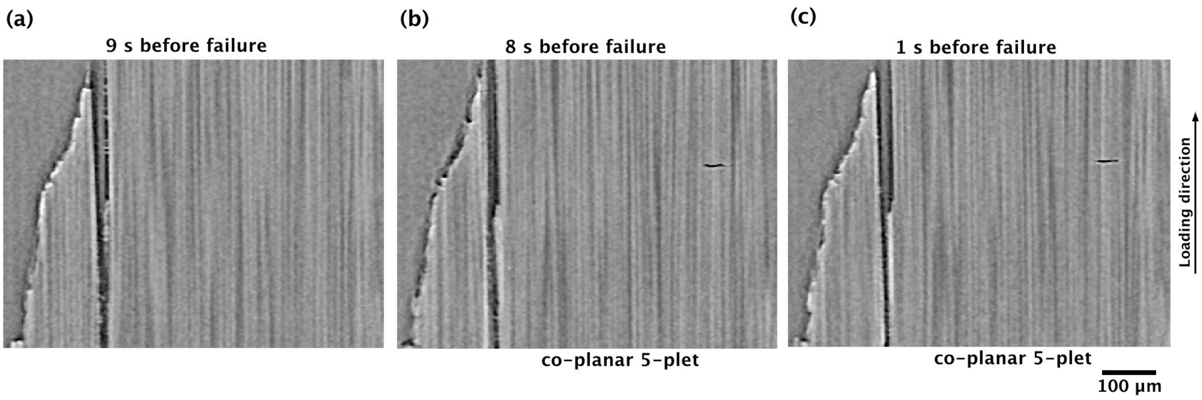

Figure 3. Fibre breaks accumulation immediately before failure: (a) 9 seconds before, (b) 8 seconds before and (c) 1 second before. The damage detected along the loading direction is a 0 ply split originated from the notch.

Multiple fragmentations, up to a maximum of 8 breaks, in single fibres were observed along the axial direction. However, most of these fragments did not show any change during these dynamic scans, suggesting that they occurred in correspondence of lower loads. Figure 4 shows an example of multiple fibre fragmentation along the axial direction for two adjacent fibres.

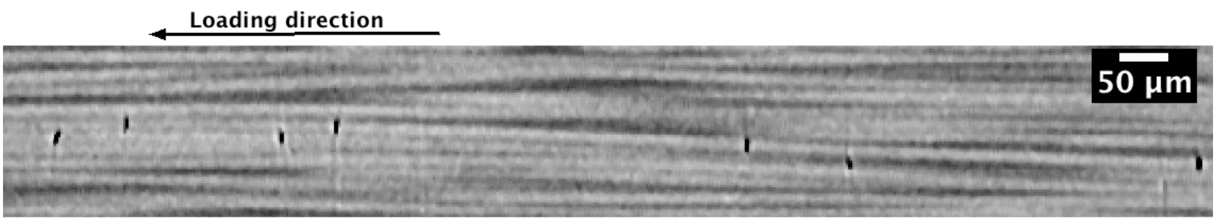

Figure 4. Multiple breaks along the same fibre observed one second before failure.

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Inspections conducted at loads between 55% UTS and 85% UTS showed that the majority of breaks along the same fibre occurred at load lower than 85% UTS. Further studies will be aimed to track axial distances between fibre breaks located on the same fibre as a function of the load.

4. Conclusions

This study highlights the advantages of using ultrafast X-ray computed tomography to monitor in real time fibre failure progression. This latter was related with 'new-born' locations rather than with the growth of pre-existing fibre breaks, both single and multiple breaks. This behaviour is consistent through all the loading increments taken into account. The majority of fibre breaks appeared as singlet and 2-plet, while multiple breaks were co-planar. Multiple axial fragmentations along one single fibre were also observed for various fibres up to a maximum of 8 breaks. Ultrafast X-ray tomography revealed to be a successful method to obtain qualitative and quantitative 4D information on fibre failure micromechanisms occurring in CFRP.

Acknowledgments

The authors would like to acknowledge Engineering and Physical Science Research Council (EPSRC) for funding the Henry Moseley X-ray Imaging Facility (grants EP/F007906/1, EP/F001452/1 and EP/I02249X/1). The authors are grateful to the Swiss Light Synchrotron Radiation for access to TOMCAT-X02DA beamline, and to the assistance Dr. Rajmund Mokso. Thanks to Dr. Ying Wang for sharing part of her beamtime, to the INSA-Lyon MATEIS to provide the loading rig used in these experiments, particularly to Dr. Eric Maire for his support during the beamtime; and to the μ-VIS at the University of Southampton.

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Excerpt from ISBN 978-3-00-053387-7