IMAGING OF COMPOSITES BY HELICAL X-RAY COMPUTED TOMOGRAPHY

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ABSTRACT

Understanding the fatigue damage mechanisms of composite materials used in wind turbine rotor blades could potentially enhance the reliability and energy efficiency of wind turbines by improving the structure design. In this paper, the fatigue damage propagating mechanisms of unidirectional glass fibre composites was characterised by helical X-ray CT. The staining approach was used and it was effective to enhance the visibility of thin matrix cracks and partly closed fibre breaks instead of widely opened cracks. Fibre breaks in the centre UD bundle were found to occur locally, instead of being evenly distributed along the 0° fibre direction after 500,000 cycles. The locations of these damage sites were found to be correlated with intersecting points of +/-80° backing bundles. At higher number of cycles, edge effect becomes dominant with extensive fibre breaks in the edge UD bundles and matrix cracks in the resin-rich region.

1 INTRODUCTION

The fatigue performance of composite materials has become a major design concerning factor, because the degradation of composite properties under cyclic loading can result in a catastrophic failure of the structural component. As a widely used material for wind turbine rotor blades, composite materials undergo a high number of cyclic loading during service [1]. Thus it is of great interest and importance to understand the damage evolution under fatigue, the key damage mechanisms and the interaction between them in composites employed in wind turbines.

X-ray computed tomography (CT), which has been increasingly applied to materials characterisation [2], is superior to other non-destructive techniques in that three-dimensional (3D) information can be obtained with a high accuracy. Unlike fatigue crack initiation and propagation in homogeneous materials, various damage mechanisms occur cooperatively in composites under cyclic loading, including matrix cracks, fibre breaks, debonding and delamination [1-5]. A 3D map of the complex fatigue damage modes in relation to local microstructure will contribute to the establishment of fatigue failure mechanisms in composites.

As observed in a number of composite systems, fatigue damage originates from thin cracks within fibre bundles or individual fibre breaks [3-5], which are on the micron level in size. High-resolution X-ray CT is essential to visualise these features, while high resolution (small voxel size) often means a small field-of-view (FOV). Using traditional X-ray CT, the information obtained along the sample length is often limited to the same dimension as its width/thickness. The use of helical X-ray CT technique provides extra volume in length direction as sample moves upwards along a helical path during scan. This is especially helpful to characterise unidirectionally reinforced fibre composites, allowing to observe overall damage and locate local micro-damage simultaneously.

In this study, the aim is to relate the distribution of fatigue damage with the composite microstructure of a glass fibre reinforced plastic (GFRP) using helical X-ray CT. The strategy of combining the staining and helical imaging approaches to visualise thin damage within a large volume was used here. This imaging strategy eases time-lapse tracking of damage evolution from arbitrary locations.

2 MATERIALS AND METHODS

2.1 Composite specimen

In the current project, the composite material studied is a glass fibre/polyester composite system used in wind-turbine blades. The GFRP has a lay-up of $[0/b]_S$, where '0' represents a 0˚ UD layer and 'b' corresponds to a thin ±80˚ backing layer. Figure 1a shows a 3D rendered CT image of the fibre architecture. The composite panel was manufactured using the vacuum assisted resin transfer moulding (VARTM) method. Specimens with dimensions of 2 mm × 5 mm × 110 mm were cut from the composite panel and GFRP tabs were added to the two ends. This miniaturised specimen geometry was used in order to obtain a higher resolution (smaller voxel size), as for the current helical CT imaging strategy the full specimen needs to be within the field of view during the scan.

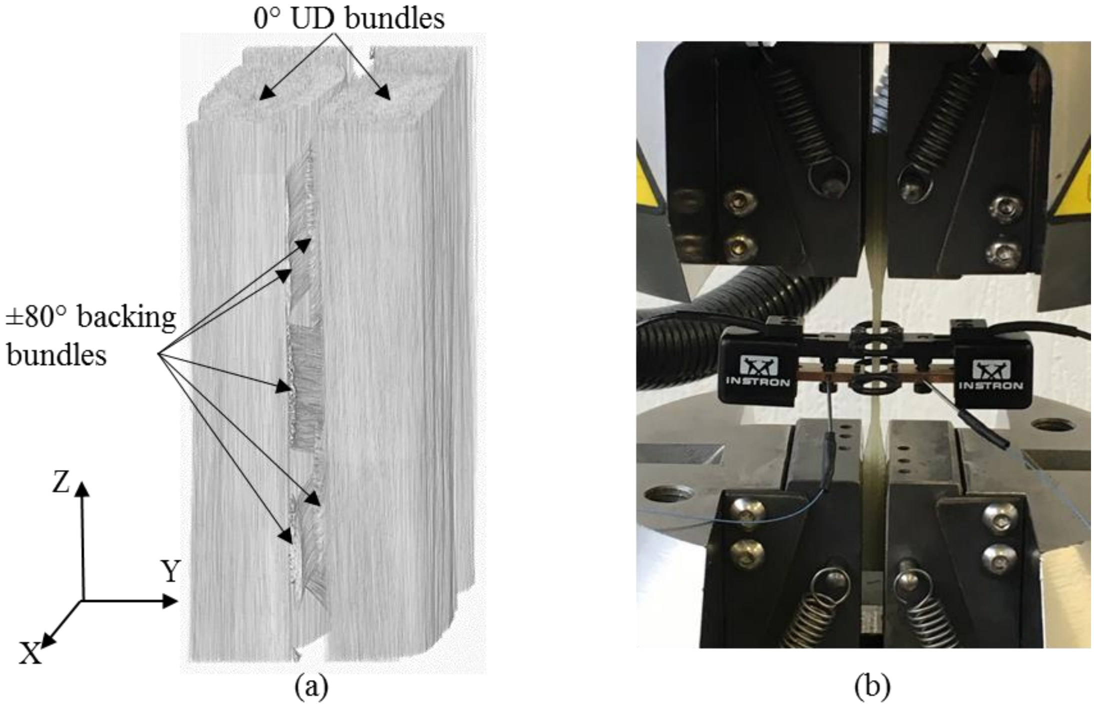

Figure 1: a) 3D rendered CT image of the composite fibre architecture, and b) Fatigue test set-up with extensometers attached onto specimen surfaces.

2.2 Fatigue testing

Fatigue tests were performed on a hydraulic Instron 8802 under load control with a sinusoidal waveform and a stress ratio (maximum stress applied divided by minimum stress) of R = 0.1 at a test frequency of 10 Hz. Two extensometers were attached to the sample surfaces to monitor the strain during fatigue (see Figure 1b). The maximum stress applied corresponds to 0.5% initial strain on the composite. The fatigue test was interrupted at different cycle number for helical X-ray CT inspection to monitor the damage evolution. The two samples discussed here were removed from loading frame at 500,000 cycles (S1) and 2 million cycles (S2) respectively. The fatigue test of specimen S1 was resumed after CT imaging and will be interrupted for ex-situ CT scans at higher cycle numbers and this is ongoing work.

2.3 Helical X-ray computed tomography

The samples were removed from the testing frame and stained in zinc iodide solution in an unloaded condition for 24 hours before being imaged on FEI HeliScan Micro-CT scanner. The source voltage was set to 80 kV and filtered by 0.1 mm stainless steel. The exposure time for each projection (radiograph) was 0.52 s. The double-helix mode was used to allow reconstruction using filtered-back-projection algorithms. During the scan, the sample stage simultaneously rotates and translates vertically following a helix path with a helical pitch of ~7.8 mm. The scanned composite volume has a height to width ratio of >3:1 at a pixel size of 2.85 um, resulting in a total scan time of ~20 hours.

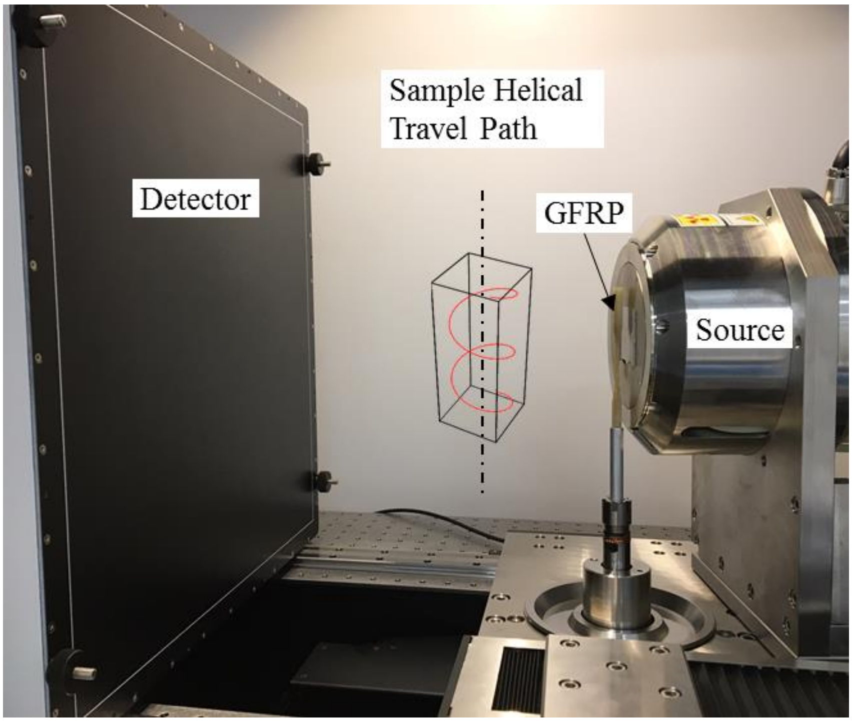

Figure 2: Helical X-ray CT imaging set-up.

3 RESULTS AND DISCUSSION

3.1 Effect of staining on damage detection

When unloaded, localised fibre breaks and matrix micro-cracks in this material system tend to be partly closed at early stages of its fatigue life, which makes it difficult to resolve damage in CT images. In this case, staining was used to enhance contrast between thin cracks and the bulk material. As the contrast agent can only penetrate into the internal damage through paths connected with sample surface, and also because of the mostly UD fibre architecture, not all of the damage could be stained. Although quantitative analysis is not reliable, qualitative analysis could be performed to explain the underlying damage mechanisms.

Staining proves effective to extract thin cracks such as the fibre breaks in UD bundles and matrix cracks (see Figure 3), which are barely observable when unstained. However, in cases where cracks are relatively opened or where fibre breaks are connected with debonding (see Figure 4), staining could make it more difficult to detect damage, either because of non-uniform penetration or over-brightness.

3.2 Overall damage distribution in relation to the microstructure

As discussed above, helical X-ray CT allows visualising damage distribution over a relatively long region. Using traditional X-ray CT, it is challenging and time-consuming to locate the region-of-interest to perform time-lapse study to track the damage evolution due to the limited FOV along UD fibre direction it. Using helical X-ray CT, the overall damage distribution in relation to the composite microstructure (eg. backing fibre bundle intersecting points, resin-rich regions, fibre misalignment in UD bundles) can be mapped through its fatigue life in a straightforward way.

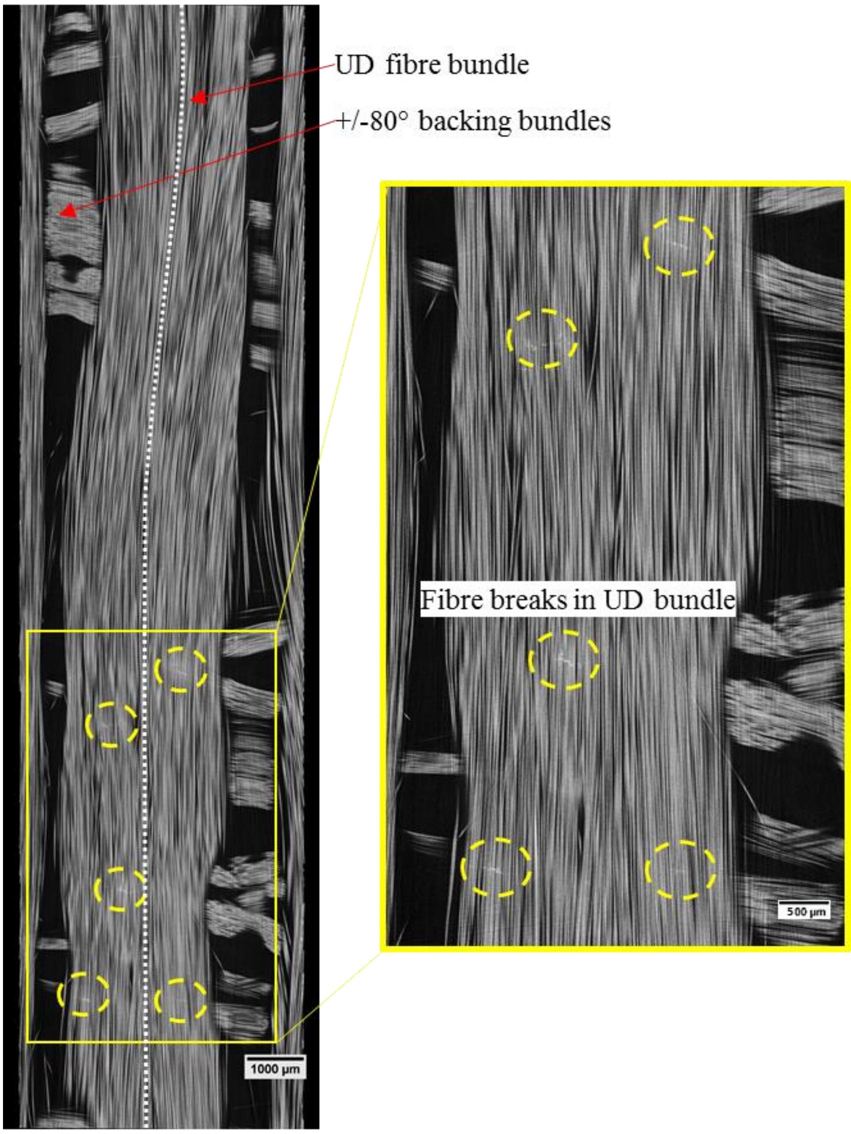

Figure 3: Helical X-ray CT virtual slice image of glass fibre composite after 500,000 tension-tension fatigue cycles showing the distribution of localised fibre breaks (highlighted in ellipses) in UD layer close to the backing layer.

In this material system, fibre breaks in the centre UD bundle were found to occur locally, instead of being evenly distributed along the 0° fibre direction after 500,000 cycles (S1). Figure 3 (a) shows a localised fibre-break rich region with five clusters of fibre breaks within ~6 mm along the 0° fibre direction. The fibre fracture surfaces did not tend to form smooth planes, but the overall trend was to align with the adjacent backing fibre direction. Previous studies have shown that in a similar material system, localised damage often occurred in regions where intersecting points of +/-80° backing bundles are in contact with the UD fibre bundles [2]. This trend has also been observed here. Moreover, at this stage fibre breaks were not found at the other 0/b inter-layer region, indicating uneven damage initiation in the two symmetrical 0/b regions. This could be partly due to the fact that the UD fibre bundle with fibre breaks is waved as indicated in Figure 3a, while the UD fibre bundle on the other side is well aligned with the loading direction. At higher number of cycles (S1 fatigued 2 million cycles), edge effect becomes dominant with extensive fibre breaks in the UD bundles at sample edges and matrix cracks in the resin-rich region between the edge and the middle UD bundles. Step-shaped fibre breaks connected by debonding as shown in Figure 4(b) occur within misaligned edge UD bundle. In regions with aligned fibres, fibre breaks are localised but randomly located as shown in Figure 4(c). Nevertheless, damage in the centre UD bundle did not propagate as much as that in the edge bundles. Ex-situ study of specimen S1 is on-going work to track the damage propagating mechanisms.

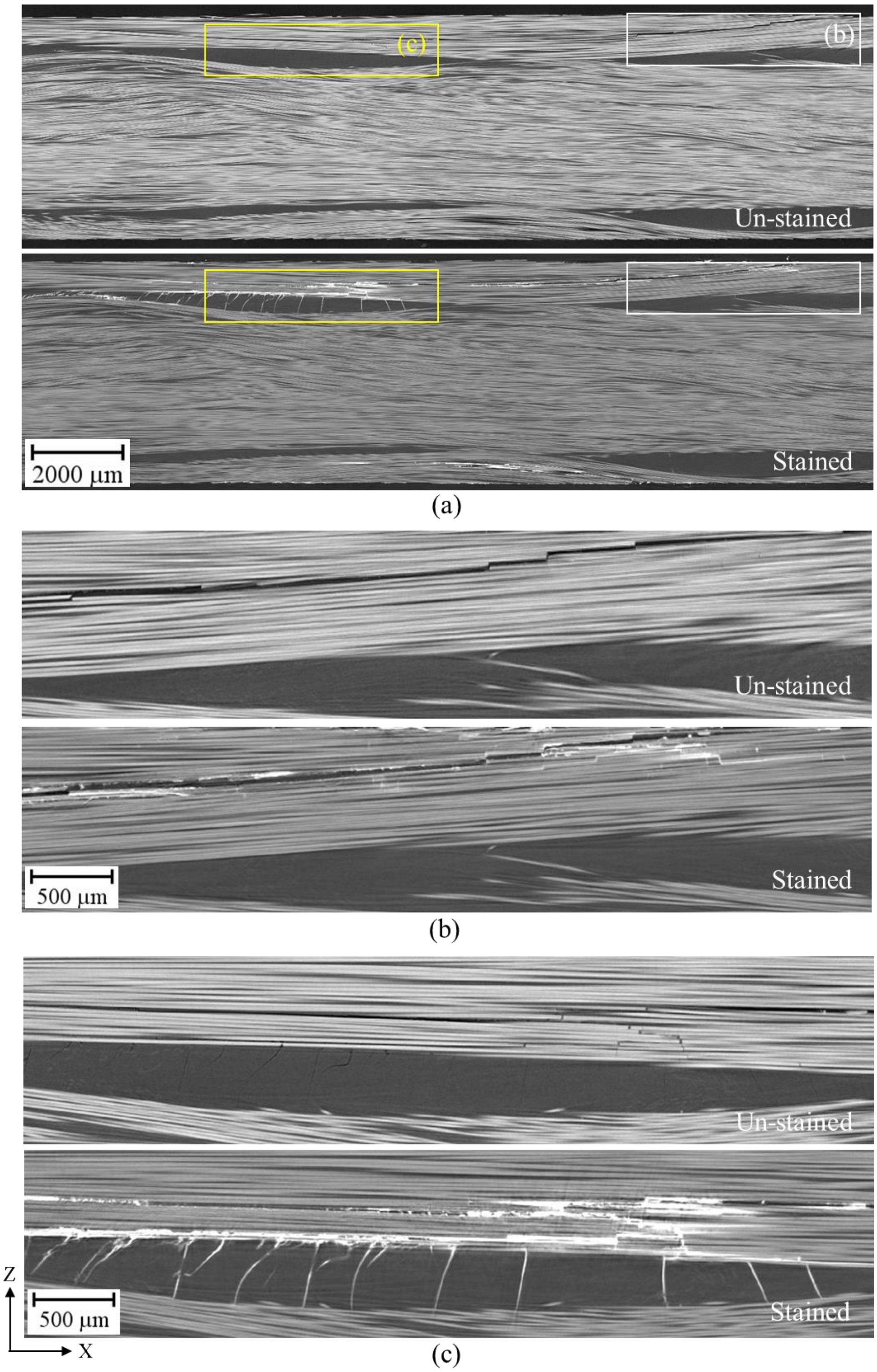

Figure 4: Helical X-ray CT virtual slice image of glass fibre composite after 2 million tension-tension fatigue cycles showing the effect of staining on detecting different damage modes.

4 CONCLUSIONS

In this study, helical X-ray CT imaging technique was used to characterise fatigue damage in unidirectional glass fibre composites. The staining approach proves effective to enhance the detectability of thin matrix cracks and partly closed fibre breaks instead of widely opened cracks. Fibre breaks in the centre UD bundle were found to occur locally, instead of being evenly distributed along the 0° fibre direction. The fibre fracture surfaces tend to align with the adjacent backing fibre direction. The locations of these damage sites were found to be correlated with intersecting points of +/-80° backing bundles. With increasing number of cycle, edge effect becomes dominant with extensive fibre breaks in the edge UD bundles and matrix cracks in the resin-rich region. Future work is required to verify the damage development mechanism using time-lapse ex-situ helical imaging.

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REFERENCES

[1] J. F. Manwell, J. G. McGowan and A. L. Rogers, *Wind turbine materials and components*, Wind energy explained: theory, design and application, 2nd edition, John Wiley and Sons, Chichester, 2010.

[2] Y. Wang, S. C. Garcea and P. J. Withers, *Computed Tomography of Composites*, Reference Module in Materials Science and Materials Engineering, Elsevier, 2017 (doi:10.1016/B978-0-12-803581-8.10250-4).

[3] K. M. Jespersen, J. Zangenberg, T. Lowe, P. J. Withers and L. P. Mikkelsen, Fatigue damage assessment of uni-directional non-crimp fabric reinforced polyester composite using X-ray computed tomography, *Composites Science and Technology*, **136**, 2016, pp. 94-103 (doi: 10.1016/j.compscitech.2016.10.006).

[4] B. Yu, R. Blanc, C. Soutis and P. J. Withers, Evolution of damage during the fatigue of 3D woven glass-fibre reinforced composites subjected to tension–tension loading observed by time-lapse X-ray tomography, *Composites Part A: Applied Science and Manufacturing*, **82**, 2016, pp.279-290 (doi: 10.1016/j.compositesa.2015.09.001).

[5] S. C. Garcea, I. Sinclair and S. M. Spearing, In situ synchrotron tomographic evaluation of the effect of toughening strategies on fatigue micromechanisms in carbon fibre reinforced polymers, *Composites Science and Technology*, **109**, 2015, pp.32-39 (doi: 10.1016/j.compscitech.2015.01.012).