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MICROMECHANICAL TIME-LAPSE X-RAY CT STUDY OF FATIGUE DAMAGE IN UNI-DIRECTIONAL FIBRE COMPOSITES

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ABSTRACT

This study considers fatigue damage evolution in a uni-directional (UD) glass fibre composite used for wind turbine blades which is manufactured from a non-crimp fabric. It is the initial part of a time-lapse study where the damage progression is followed in a sample during a fatigue test. In the current study 3D X-ray Computed Tomography (XCT) is used to characterise the fatigue damage in the material at three different stages of the fatigue life of a tension-tension fatigue test. 3D XCT is performed on rectangular samples (4x4x110mm) cut out from pre-fatigued full-size fatigue test specimens. The geometry of the cut-out is similar to that which will be used in the time-lapse study.

As the micro-mechanical damage mechanisms are small features, it is necessary to obtain a high scan resolution which sets a limit to how large the field of view can be. Therefore, it is necessary to perform several scans on each sample to locate damaged regions even for the cut out sample geometry. For the chosen down-scaled sample geometry it was possible to visualize individual broken UD fibres, matrix cracks, and delaminations in the scans. Broken UD fibres are observed locally close to intertwining regions of the supporting backing bundles where they are in direct contact with the UD bundles. Additionally matrix cracks are observed in the off-axis backing layer at locations where the UD fibres are broken.

1 INTRODUCTION

Wind turbine blades are subjected to a high number of load cycles during the life-time of the wind turbine. During the turbine’s 20-30 years of life, it is subjected to fatigue loading in the range of 10^9 cycles caused by variation in the wind and the blade weight combined with the rotation. The wind causes repeated flap-wise bending of the blade, and the rotation causes repeated edge-wise bending of the blade. UD composite materials are used to carry the main bending loads in the blade and the fatigue damage mechanisms in this type of composite is not very well understood. Since fatigue is one of the main limiting design factors, it is of great interest to understand fatigue mechanisms of these UD composites [1,2]. The current study considers tension-tension fatigue damage evolution in a UD non-crimp fabric glass fibre composite similar to those used for wind turbine blades. The fatigue damage evolution on a micro-structural level is studied using the non-destructive imaging technique 3D XCT imaging.

1.1 Fatigue of composites

Various failure modes occur and interact during fatigue in a composite material such as; fibre/matrix debonding, matrix cracking, delamination, and fibre breaks [3]. Because of the complexity of the fatigue damage mechanisms in composite materials, it is not fully understood. Several studies have tried to relate the crack density with the material properties [3-5], however most of these studies disregard fibre fracture in the 0 degree layers and only consider cracks in the off-axis layers of the composite.

Zangenberg et al. [6] examined a UD non-crimp glass fibre composite by means of scanning electron microscopy (SEM), optical microscopy, and resin burn-off techniques to characterize the tension-tension fatigue damage. Based on these studies, it was found that the damage initiates in the supporting off-axis backing layers, and then progresses into the load carrying UD layers, causing UD fibres to break. The techniques used in these studies, however, are all destructive techniques and polishing and grinding of the samples can also introduce further damage to the samples. Since the techniques are destructive, the study only considered one point in time. Furthermore, the imaging techniques only provide 2D images, which only give a partial image of how the damage looks, since it is a 3D feature. An alternative to these examination techniques is 3D XCT, which also sometimes is referred to as x-ray micro-tomography for the resolution in the micro-scale.

1.2 XCT imaging of damage in composite materials

XCT is a non-destructive imaging technique where the sample is placed between an x-ray source and a detector. X-rays are emitted from the source through the sample giving a projection image on the detector. The sample is then rotated in steps and a projection image is stored for each rotational step. A reconstruction algorithm is used to reconstruct a 3D visualization of the volume considered. The contrast in the image is related to the atomic density of the materials, and therefore some materials can be difficult to tell apart in the images. [13] The difference between the atomic densities of the glass fibres and matrix material is around a factor of 2, giving a good contrast in the image. Despite the high contrast, it is challenging to see damage in the material if the cracks are closed (the crack faces in contact).

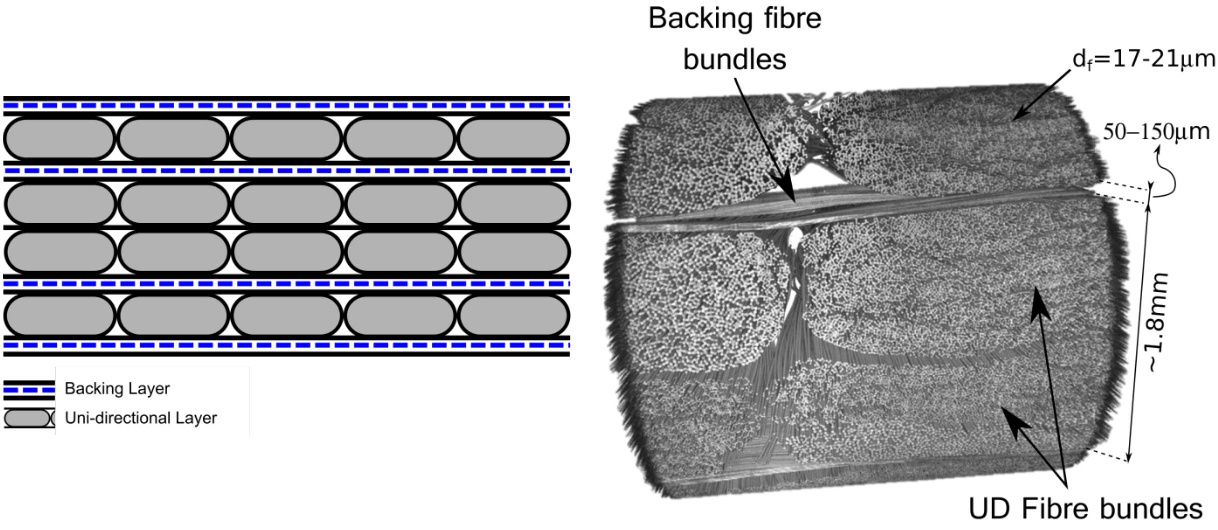
XCT is becoming an increasingly popular technique for materials characterization, and it has also begun to receive attention in the characterisation of composite materials. In order to visualize the damage mechanisms in composites on a micro-structural level, a high resolution is required. Therefore studies considering individual fibre breaks are mainly carried out using synchrotron radiation and by having small samples (thickness a width of a few millimetres) [7-10]. Only limited work has been carried out considering damage in composite materials examined using a commercial x-ray micro-tomography system [11,12]. In [11] a range of composites were studied using a commercial XCT Instrument, however with small sample sizes and a minimum voxel size of 3.7 microns for a cross section of 1.8x1.4mm. Individual fibre fracture was not considered, probably because of a lack of resolution.

In this initial study, full size fatigue tests are performed on several specimens, and the tests are stopped at different damage stages. The full size fatigue test specimens are then cut into smaller, down-scaled specimens on which XCT is performed. The damage mechanisms which can be detected in the down-scaled specimens are outlined and some challenges related to the future in-situ time-lapse experiments are discussed. Finally, the observed damage at around half-life time and close to final failure is compared.

2 EXPERIMENTAL

2.1 Material and sample geometry

The material considered is a composite manufactured from a UD non-crimp glass fibre fabric and a thermoset polyester resin. Each UD layer (0 degree) consist of fibre bundles which are stitched to a layer of thin layer of supporting off-axis backing bundles. The stacking sequence of the considered material is [b/0,b/0]s where b represents the backing layers. Figure 1a shows an illustration of the material layup, and Figure 1b shows a 3D representation of the microstructure obtained from 3D XCT including approximate dimensions.



(a) (b)

Figure 1: The stacking sequence of the considered composite (a) and an example of the real microstructure from 3D XCT with approximate dimensions (b).

The composite was manufactured by vacuum assisted resin transfer moulding (VARTM) infusion. A butterfly geometry specifically optimized for fatigue testing of UD composites was used for the fatigue tests. The geometry is shown in Figure 2 and is used to avoid failure outside the gauge region since the load is transferred into the sample through shear. For more information about this test geometry, see [2]. Figure 2 also indicates the approximate location of the cut-out used for the x-ray CT imaging, which is further discussed in the next section.

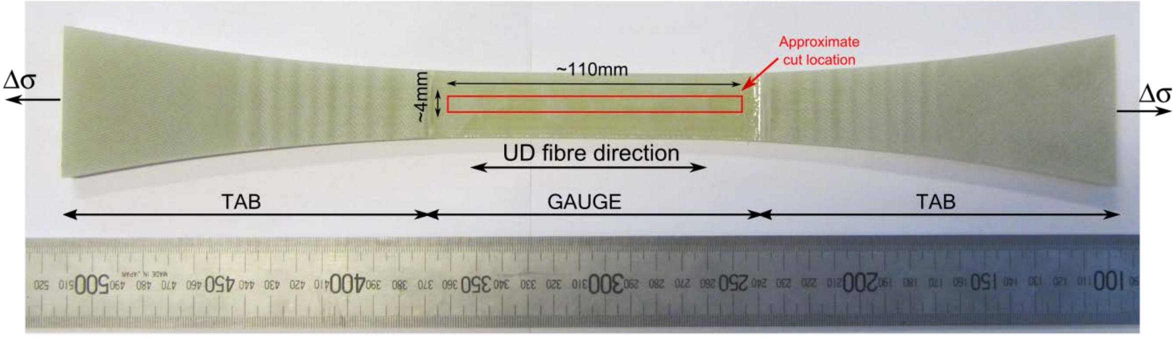


Figure 2: Butterfly specimen geometry used for fatigue tests (410 mm long). The red square indicates the approximate cut location of the samples scanned using 3D XCT.

2.2 Fatigue loading and cut-out of samples

Fatigue tests were carried out on several butterfly specimens using an Instron 8800 hydraulic machine. A few tests were run until fracture to have an idea about when to stop the remaining tests. Figure 3 shows the typical stiffness degradation curve for this type of composite. The current study considered three tests stopped at different locations, as indicated in the figure. The locations were chosen at positions where the curve shows a different behaviour; in the initial stiffness drop region, in the linear region, and in the final localisation phase.

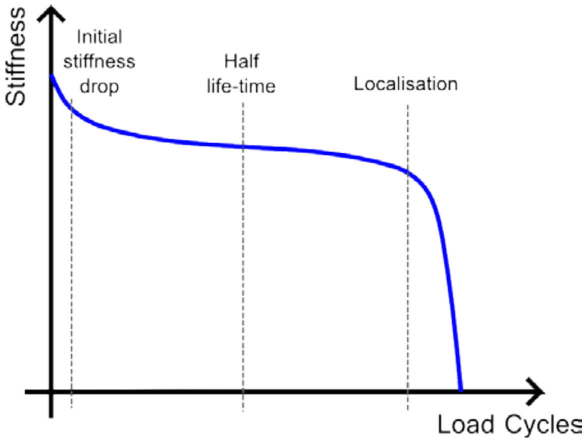


Figure 3: Typical stiffness degradation behaviour of considered composite. Approximate locations of the stopped fatigue tests are indicated on the figure.

The fatigued samples were cut into rectangular shaped specimens using a diamond blade. The specimens were cut to a size of 4x4x110mm.

2.3 X-ray Computed Tomography

In this study the Zeiss Xradia Versa 520 system was used to perform the XCT experiments. The sample was rotated 360 degrees during the tomography. The software “XMReconstructor – Cone Beam 10” by Zeiss was used for reconstruction and “AVIZO 9.0” by FEI was used for visualization and manual segmentation of fibre fractures. Performing XCT scans is always a balance between the FOV size and the resolution, as increasing the size of the field of view (FOV) also increases the voxel size. Since the internal micro-structural damage consists of small features, a high resolution is necessary. Therefore the samples were scanned with a small FOV using the settings shown in Table 1.

Optical Magnification	Source to sample distance [mm]	Detector to sample distance [mm]	Pixel size [µm]	Field of view on detector [mm]
3.98 (4X)	11	20	1.2	2.4x2.4

Table 1: Settings for the performed XCT

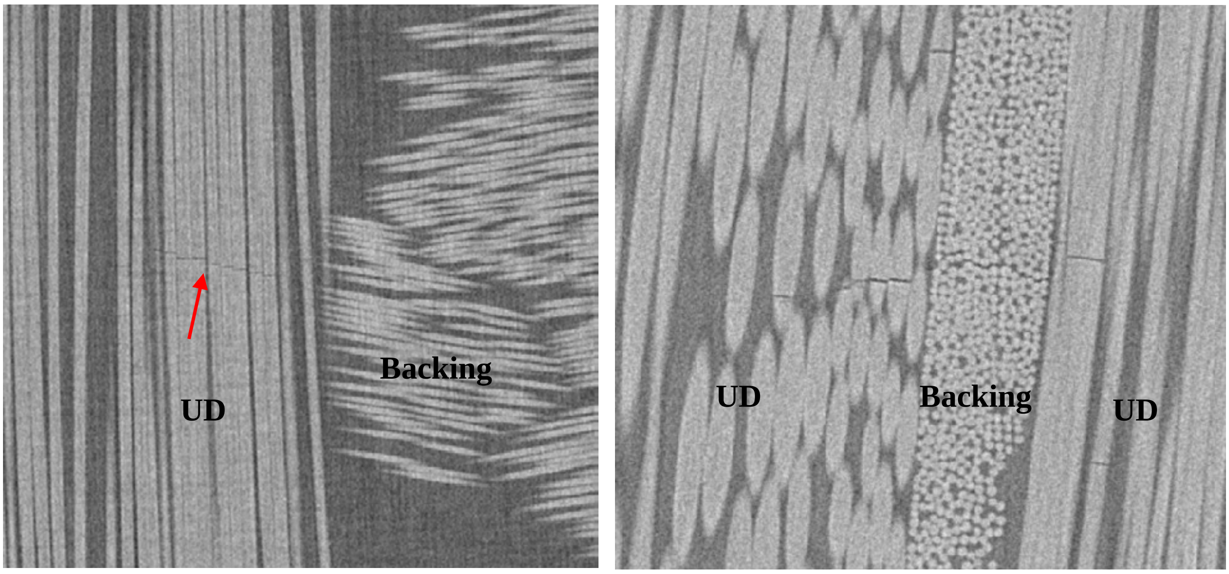
Since broken fibres are not equally spread in the volume, it can be a bit of a hit and miss to locate a region with broken fibres when considering such a small region. For that reason scans are performed at multiple positions in the samples.

3 RESULTS AND DISCUSSIONS

Scans were performed on fatigued samples stopped at the locations shown in Figure 3. No damage was observed in the sample stopped in the “initial stiffness drop”. It would be expected to see matrix cracks in the backing and at the current resolution their presence cannot be ruled out. For the "half life-time" sample, only a few broken fibres were observed. The scan of the sample stopped at "localization" showed various damage mechanisms in the scans such as fibre breaks, matrix cracks, and matrix/fibre delamination. The examples of observed damage shown in the following are from the "localization" sample.

3.1 Observed damage mechanisms

In the performed 3D XCT imaging of the fatigued specimens, several damage mechanisms were observed. Figure 4a shows an example of observed UD fibre breaks when looking parallel to the UD fibres. The image shows the fibres locally closest to the backing layer, and it is seen that the broken fibres are aligned with the backing fibre direction. This indicates that the fractures are caused by a matrix crack in the backing. Additionally Figure 4b shows a view perpendicular to the backing fibres, where broken UD fibres are observed locally close to the backing. It is seen that a matrix crack has penetrated through the two intertwining backing bundles, which is likely to have initiated the fibre breaks in the UD bundles next to it. The fibres on the left side of the backing bundles are highly misaligned in this case. The matrix crack in the backing bundle is only just visible at this resolution since the contrast between the matrix and air is limited. Because of this it cannot be ruled out that matrix cracks are present at other locations as well, where the opening is smaller than in this example.



(a) (b)

Figure 4: Broken load carrying UD fibres locally close to the backing. The UD fibres are seen to break in a line aligned with the backing fibre direction (a), and broken UD fibres are seen next to a matrix crack in the backing bundle (b).

Aside from fibre breaks and cracks in the backing layers, large matrix cracks were observed in the large resin rich zones where the UD bundles meet, as seen in Figure 5a. The matrix cracks occur with a slight variation in spacing and are in contact with the backing. Similar matrix cracks are also observed at the outer surface of the sample as seen in Figure 5b. The matrix cracks are observed to span from the outer sample surface and into the backing bundles close to the surface. It seems that these cracks are related to the presence of the backing, and not all of them span to the sample surface. Therefore, it seems likely that these cracks have initiated from cracks in the backing.

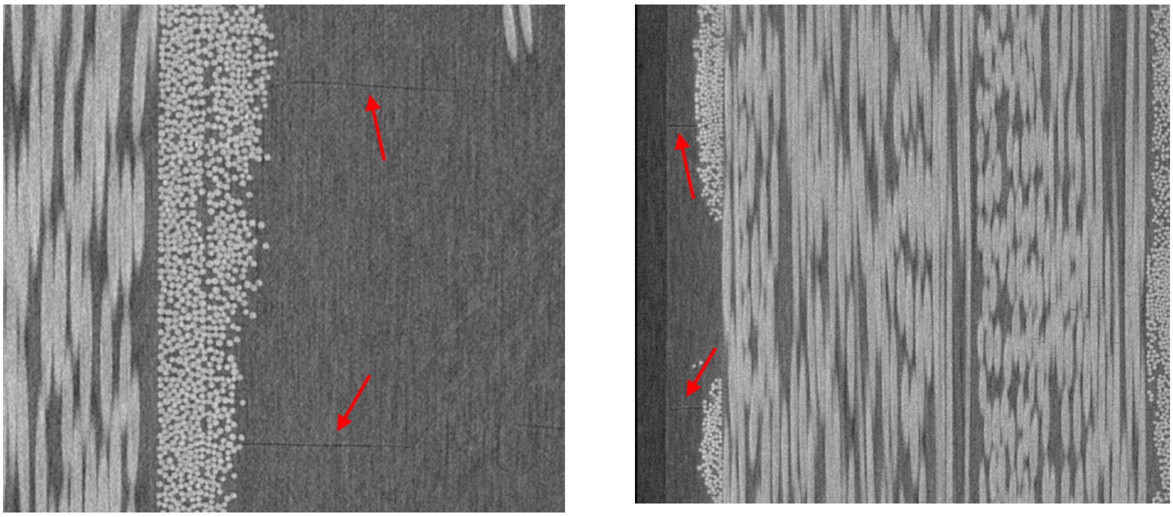

(a) (b)

Figure 5: Transverse matrix cracks at backing in the resin rich zones between UD bundles (a) and matrix cracks at sample surface at backing bundles (b).

Additionally matrix cracking (or fibre/matrix debonding) was observed in the UD bundle as seen in Figure 6. It looks like a matrix crack from the resin rich zone has progressed into the UD bundle and caused the delamination. From the zoomed in image in Figure 6b it could look like that the matrix crack is progressing around the stitching thread which has the same contrast as the matrix material.

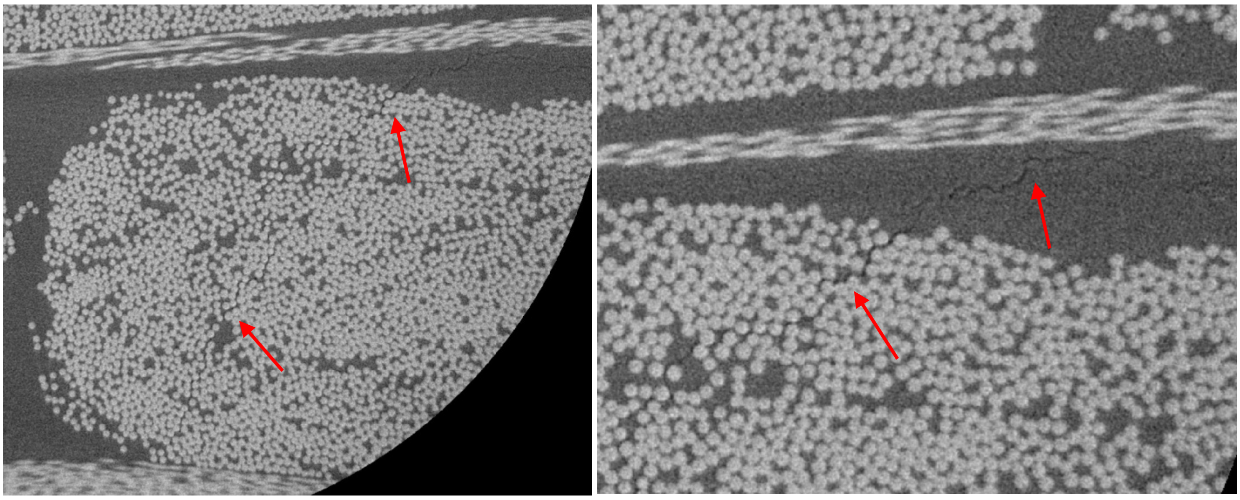
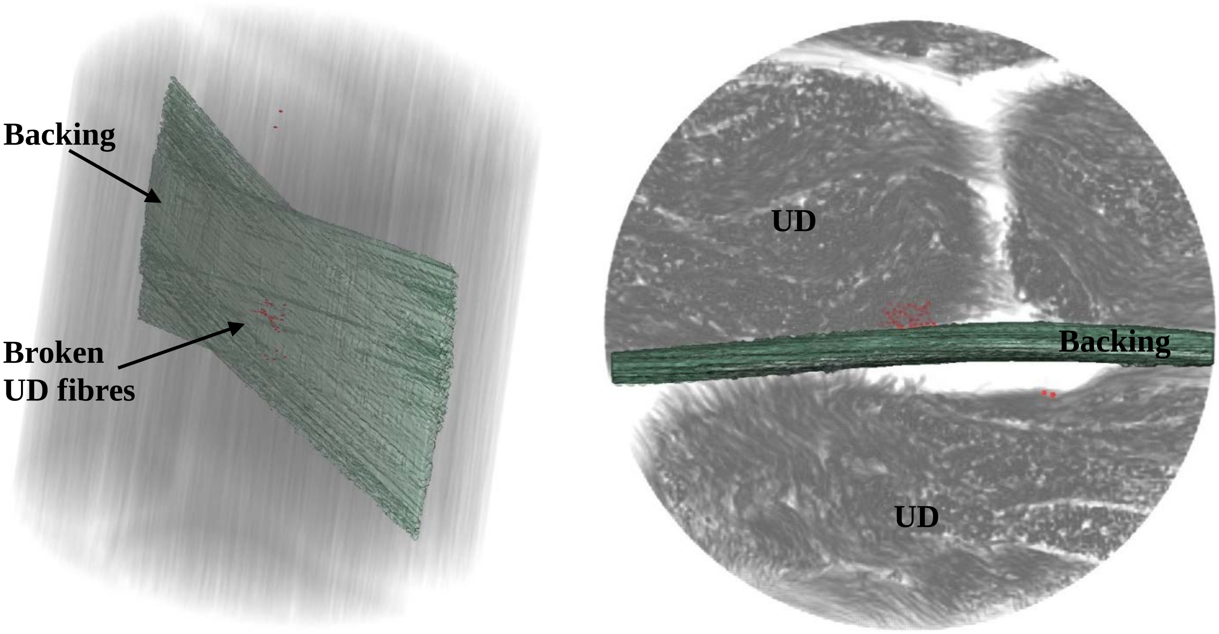

(a) Whole crack (b) Zoom

Figure 6: Matrix crack spanning from matrix and through UD bundle. The matrix rich zone is likely to include stitching thread which has the same contrast as the matrix.

3.2 Damage visualization and comparison

As also observed in previous studies by Zangenberg et al. [6], the damage evolution was observed to be dependent on the interaction between the transverse backing bundles and the UD fibres. If the backing bundles are crossing each other and at the same time are in direct contact with a UD bundle, broken fibres are observed in this region after tension fatigue loading. However, this also means that in regions where this is not the case, broken fibres are not likely to be observed. Since the XCT scans have a fairly small field of view, it can be difficult to target the correct location. In this study it was chosen to scan multiple regions where it looked like a backing layer was present in the 2D projection image. At locations where the bundles were not in direct contact or only a single backing bundle was present, no broken fibres were observed in the scans.

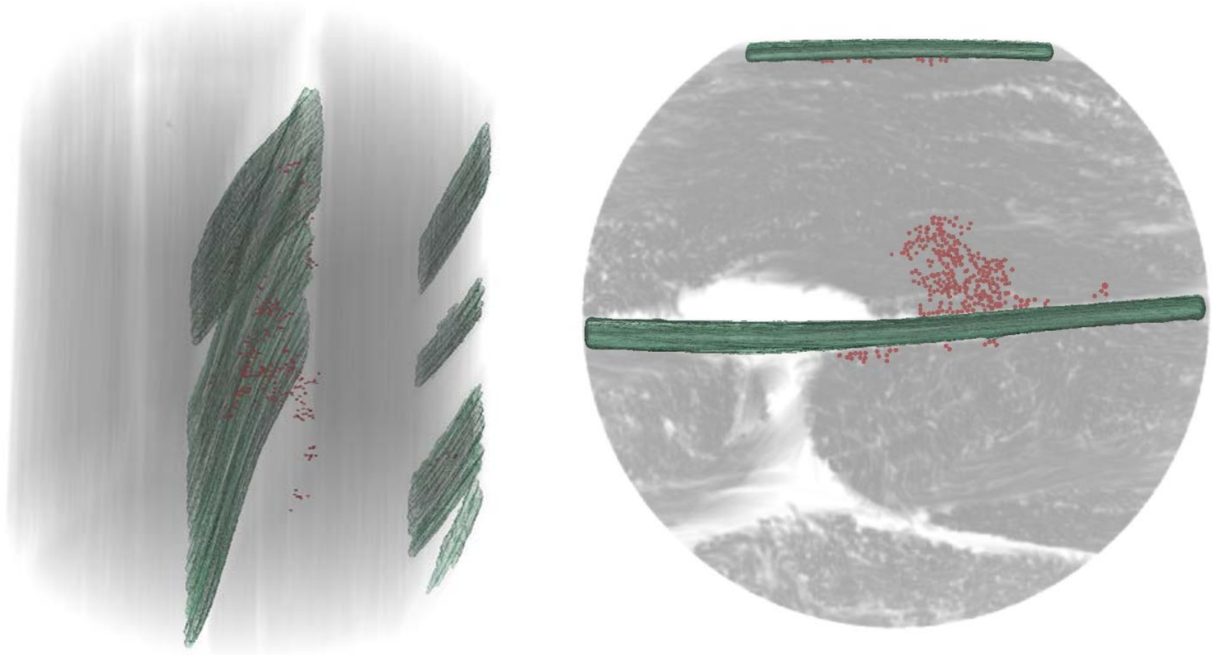
Figure 7 shows 3D segmentation of the broken UD fibres relative to the backing (green) for a sample subjected to half life-time where the broken fibres are marked as red discs. The fibres were manually segmented by eye, to give a volumetric visualization of the distribution of the broken fibres. Work is ongoing on developing an automated method for locating the UD fibre fractures.



(a) 3D View (b) Top view

Figure 7: Distribution of broken UD fibres in scan performed on the sample subjected until around half life-time. The broken fibres are marked by red discs in the UD bundles which are shown as transparent light grey. The backing bundles are marked in green.

It is seen from Figure 7 that a few broken fibres exist locally close to the double backing layer, which is in contact with the UD bundle. The backing and the UD bundles are only in contact on one side, and broken fibres are only observed on this side. Figure 8 shows a similar view of the material subjected to almost full fatigue life.



(a) 3D View (b) Top view

Figure 8: Distribution of broken fibres in scan performed on the sample subjected until damage localisation. The broken fibres are marked by red discs in the UD bundles which are shown as transparent light grey. The backing bundles are marked in green.

In the Figure 8 it is seen that there are a lot more broken fibres near the backing. Additionally, it is seen that the broken fibres have spread out into an area around the initiation from the backing. Broken fibres are observed to spread out in the UD fibre direction at some distance away from the backing. It should be noted that the damage in the two shown cases are for two different samples which means that they cannot be directly compared. Despite this, it gives a good idea of how the damage progresses in the sample. Additionally it serves as a good basis for comparison when performing the down-scaled time-lapse fatigue experiment.

4 CONCLUSIONS

The current study has shown that micro-structural damage in terms of fibre fracture and some matrix and delamination cracks can be visualized using laboratory XCT imaging. Broken UD fibres are observed locally at the supporting transverse backing layers at intertwining regions in direct contact with the UD bundles. For the UD fibres closest to the intertwining backing bundles in direct contact with the UD bundle, broken fibres initiate in a row parallel to the backing fibres. Additionally matrix cracks in the backing bundles are seen to be present at some of the locations of the broken fibres. This indicates that the broken fibres are initiated by cracks in the backing bundles.

A difference was observed in the broken fibre damage between a sample subjected to half life-time and close to localization. However the study considered the damage in different samples, and it cannot be ruled out that other locations would have more/less broken fibres than the ones discovered. Therefore a direct comparison between the two examples might not be reasonable. The current study provides a good basis for future time-lapse studies on down-scaled test specimens. From time-lapse it will be possible to compare the damage mechanisms observed in the fatigue tests performed on down-scaled specimens with the results of the current study, as the tests here were performed on “full-size” fatigue test specimens. This will support the validity of the results obtained in the future time-lapse fatigue experiments.

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REFERENCES

[1] R. P. L. Nijssen, Fatigue life prediction and strength degradation of wind turbine rotor blade composites, *Ph. D. Thesis,* Delft University of Technology, 2006.

[2] J. Z. Hansen, The effects of fibre architecture on fatigue life-time of composite materials, *Ph. D. Thesis*, DTU Wind Energy, 2013, no. 0018(EN)

[3] F. E. Edgren, D. Mattson, Leif E. Asp, and Janis Varna, Formation of damage and its effects on non-crimp fabric reinforced composites loaded in tension, *Composites Science and Technology*, **64**, 2004, pp. 675-692 (doi: 10.1016/S0266-3538(03)00292-6).

[4] A. Gagel, D. Lange, and K. Schulte, On the relation between crack densities, stiffness degradation, and surface temperature distribution of tensile fatigue loaded glass-fibre non-crimp-fabric reinforced epoxy, *Composites part A: applied science and manufacturing,* **37(2)**, 2006, pp. 222-228 (doi: 10.1016/S0266-3538(03)00292-6).

[5] D. Song and Nubuo Otani, Fatigue life prediction of cross-ply composite laminates, *Materials science and engineering A – Stuctural materials properties microstructure and processing*, **238(2)**, 1997, pp. 329-335.

[6] J. Zangenberg, P. Brøndsted, J. W. Gillespie Jr., Fatigue damage propagation in unidirectional glass fibre reinforced composites made of a non-crimp fabric, *Journal of Composite Materials*, **48(22)**, 2014, pp. 2711-2727 (doi: 10.1177/0021998313502062).

[7] P. Wright, X. Fu, I. Sinclair, and S.M. Spearing, Ultra high resolution computed tomography of damage in notched carbon fiber-epoxy composites, *Journal of Composite Materials*, **42(19)**, 2008, pp. 1993-2002 (doi: 10.1177/0021998308092211).

[8] P. Wright, A. Moffat, I. Sinclair, S.M. Spearing, High resolution tomographic imaging and modelling of notch tip damage in a laminated composite, *Composites Science and Technology*, **70(10)**, 2010, pp. 1444-1452 (doi: 10.1016/j.compscitech.2010.04.012).

[9] A. E. Scott, M. Mavrogordato, P. Wright, I. Sinclair, S. M. Spearing, In situ fibre fracture measurement in carbon-epoxy laminates using high resolution computed tomography, *Composites Science and Technology*, **71(12)**, 2011, pp. 1471-1477 (doi: 10.1016/j.compscitech.2011.06.004).

[10] S.C. Garcea, M.N. Mavrogordato, A.E. Scott, I. Sinclair, S.M. Spearing, Fatigue micromechanism characterization in carbon fibre reinforced polymers using synchrotron radiation computed tomography, *Composites Science and Technology*, **99**, 2014, pp. 23-30 (doi: 10.1016/j.compscitech.2014.05.006).

[11] Paul J. Schilling, BhanuPrakash R. Karedla, Arun K. Tatiparthi, Melody A. Verges, Paul D. Herrington, X-ray computed microtomography of internal damage in fiber reinforced polymer matrix composites, *Composites Science and Technology*, **65**, 2005, pp. 2071-2078 (doi: 10.1016/j.compscitech.2005.05.014).

[12] F. Sket, R. Seltzer, J.M. Molina-Aldareguía, C. Gonzalez, J. LLorca, Melody A. Verges, Paul D. Herrington, Determination of damage micromechanics and fracture resistance of glass fiber/epoxy cross-ply laminate by means of X-ray computed microtomography, *Composites Science and Technology*, **72(2)**, 2012, pp. 350-359 (doi: 10.1016/j.compscitech.2011.11.025).

[13] J. Banhart, *Advanced Tomographic Methods in Materials Research and Engineering,* Oxford Univ. Press, pp. 480, 2008.