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Observing the evolution of fatigue damage and associated strain fields in a correlative, multiscale 3D time-lapse study of quasi-unidirectional glass fibre composites

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Abstract. This research is focused on studying the tension-tension fatigue behaviour of a unidirectional (UD) glass-fibre wind turbine composite. The damage features, their progression and the associated strain fields are tracked in a representative volume by employing a novel correlative approach bringing together x-ray computed tomography (XCT) and digital image correlation (DIC). The focus is on studying ex situ the evolution of damage features (fibre breaks and micro cracks) in an interrupted time-lapse manner. The major drops in stiffness are correlated to the number and location of the damage features in the bulk (XCT) and at the surface (DIC). Results from XCT highlight a localized cluster of fibre breaks and matrix cracks near backing bundles along with axial macro-cracks, while DIC shows that the backing bundles cause regions of higher strain. This highlights the relation between the damage features and strain localisation and their effect on the progressive degradation in stiffness during high cycle fatigue (HCF) cycling.

1. Introduction

With the global call for increasing investment in, and exploitation of, renewable resources owing to environmental damage manifest as climate change, wind energy remains a strong candidate for the shift of power generation from fossil fuel-based resources to renewable and more environmentally sustainable ones [1]. Over recent years there has been a strong increase in the installation and production capacity of wind farms worldwide [2]. As the wind power generated by a turbine is proportional to the swept area by the rotor blades, there is a clear drive towards longer, larger and thus heavier blades, increasing the strength and fatigue life requirements.

The spar caps, which are the main load-bearing components in the blades, are made of quasi-unidirectional glass and carbon fibre reinforced composites, which experience a high-cycle fatigue (HCF) loading regime, having a service life as high as 30 years encompassing $10^6$-$10^9$ cycles [3]. These materials are selected because of their optimum balance between cost, high stiffness-weight ratio, fatigue resistance and design flexibility. Furthermore considerable performance improvements have been achieved for such composites over the last decade increasing their range of applications [4].
The blades are subjected to repeat edge-wise and flap-wise oscillating loading from the weight plus the centrifugal rotation and wind dynamics respectively, which essentially engage the load bearing glass fiber composites in a fatigue regime.

As a result of the fatigue damage accumulated the blade gradually loses its working stiffness which in extreme cases can even lead to collision with the supporting tower or even catastrophic failure. Consequently, the focus of this study is to understand how loads representative of such cycles affect the mechanical properties over the service life, observing the effect it has on the microstructure and how that builds up over time to affect the macro mechanical response of these materials. This will help us isolate key factors in the microstructure which are critical to this behavior and help us optimize them to improve the mechanical response, both in terms of extending the safe service life and achieving a higher load bearing capacity.

The fatigue behavior of unidirectional composites has been an active area of research since the 70s, inspired initially by the metal fatigue experience, but then slowly moving to accommodate other important aspects of the microstructure, especially the interfacial phenomena between the fibers and the matrix [5], [6]. ‘Fatigue life diagrams’ [7] can be used to lay out the progressive and non-progressive governing mechanisms in the fatigue regime, thereby helping to identify which zones of distinct damage features in the diagram are critical to failure. In general, the dominant damage features on the micro scale include, among others, fibre breaks, fibre-matrix debonding, matrix yielding and cracking, and transverse ply cracking. This leads to complex modes of damage progression which are challenging to predict accurately, especially for different layups. Quasi-unidirectional (UD) non-crimp composites offer excellent unidirectional strength and stiffness and are widely used in wind turbine applications. They have the majority of fibres running in the load-bearing axis direction clustered in bundles (tows), while a small number of backing fibres run in off-axis directions. The UD bundles are tied to the backing bundles by means of stitching threads to aid integrity during laying up and manufacturing.

It has been shown [8] that in the early and intermediate stages of fatigue life, the drop in stiffness can be related to the crack densities in the matrix for materials with unidirectional fibre bundles with backing layers at ±45° and 90°. The final stage near failure involving 0° fibre rupture exhibits a rather stochastic behavior, believed to be due to stress concentrations near the tip of the intra ply matrix cracks.

It has been proposed [9,10] that the damage starts in, and near, the off-axis bundles, especially in regions which are in crossover between the UD and backing bundles, as matrix cracks and fibre breaks, and then progress towards the thickness in a diffuse manner [9,11]. As the progression is complex and essentially stochastic in the microstructure, it is difficult to predict accurately and reliably.

Recently, combined advanced imaging and characterization methods at the microscale have been put forward which are delivering new insights into the classic initiation, propagation and failure by damage evolution [12]. These include not only imaging, but other critical complementary pieces of information regarding stress-strain fields, morphology and chemistry, among others. On this front, x-ray computed tomography (XCT) has been proven particularly successful for investigating this microscale behavior since this is the scale of the onset of sensible damage, and this technique can provide 3D information non-destructively [13,14]. It can provide key insights to help resolve the complex morphology and sequencing of the damage by monitoring the damage in UD composites in a time-lapse manner during fatigue [9,10].

Digital image correlation (DIC) has been developed [15] around the 70’s in and has been used to investigate deformation in fibre composites as early as the 90’s [16]. DIC involves the tracking of a speckle pattern on the sample specimen surface to infer the displacement and associated strain fields.

In this paper these techniques are used in a complementary workflow to the study the fatigue behavior of UD composites across varying length scales.
2. Materials and Experimental Methods

2.1. Materials systems

The materials have been supplied by Saertex GmB H, comprising UD E-glass fibre bundles stitched to backing bundles (90°) and impregnated in epoxy using vacuum-assisted resin transfer molding, with a layup of [[0/90]/[90/0]], with the backing bundles adjacent to each other and none in the center sandwiched between 100 micron thick layers of cross woven fabric on either surface.

Butterfly geometry fatigue test specimens of length 284mm were cut out using waterjet with a parallel sided gauge length of 44 mm, as shown in Fig. 1.

The smallest width at the gauge was 10mm wide, with the plate thickness of 3.8 mm. End tabs of length 120mm were stuck on to avoid crushing the ends, tapered over a length of 60mm, to reduce stress concentrations.

2.2 Experimental workflow

A workflow involving time-lapse x-ray CT and digital image correlation was used to identify the progression of damaged regions and their associated strain levels through the fatigue test. Fig. 2 shows the characterization workflow aligned with the observed degradation in stiffness degradation. The central focus is to investigate the strain distribution and progression of damage features over the whole gauge as the number of cycles increase. Region I describes the initial drop in stiffness upon fatigue cycling, followed by stable response in region II, followed by a steep decrease in stage III just before failure. The fatigue tests were interrupted for DIC (in-situ) and CT (ex-situ) at 3 intermediate stages in addition to the first stage in the timeline. The region of interest for CT scanning were chosen from the strain hotspots identified from the DIC images. The sample was tested to failure but rather fatigue cycling was stopped when around 10% stiffness was lost.

Figure 1. Sample specimen cut out in a butterfly geometry. All the dimensions are in mm.

Figure 2. Schematic showing the experimental workflow scheduled around the degradation in stiffness, E, and number of cycles, N. The initial stiffness is $E_0$ and total number of cycles is $N_f$. 
2.3. Mechanical testing
The fatigue tests were carried on an Instron Servohydraulic 8802 with a 100kN load cell at maximum strain of 1.0% with a stress ratio of R=0.1, in load control with a sinusoidal waveform and 4 Hz to avoid self-heating.

The strain was monitored with both a clip-on extensometer (5mm extension/12.5 mm gauge). The stiffness was continuously tracked while the DIC images were acquired at a cycle frequency of 0.125 Hz to minimize blurring and the imaging frequency of 10 frames per second, over the whole gauge length of 44mm, for a full single cycle at all the 4 stages. The sample gauge was ‘speckled’ using a black and white spray paint, to obtain sufficient contrast between the black and white points for correlation. LaVision Strainmaster systems were used both in terms of the software and hardware for the DIC acquisition and processing.

2.4. X-ray computed tomography
XCT experiments were carried out on a Zeiss Xradia Versa 520 scanner with the sample mounted on a custom-made holder fixtured to enable it to be mounted as close in the identical location for each scan in the sequence. As has been demonstrated from [9,10], the damage starts to occur near the backing bundles, so a RoI (region of interest) containing a backing bundle was scanned. The projections were not binned. The scan settings are summarized in Table 1.

| Source to sample distance | Detector to sample distance | Optical magnification | Pixel range | Exposure time | Number of projections/tomogram | Accelerating voltage | Pixel size  |
|--------------------------|-----------------------------|-----------------------|-------------|--------------|-------------------------------|----------------------|------------|
| 42 mm                    | 150 mm                      | 4x                    | 16-bit      | 20s          | 3201                          | 70kV                 | 0.7µm      |

3. Results and discussion
The degradation in stiffness over time is shown in Fig. 3, with the key points marked. The degradation in stiffness can be divided into 3 regions in accord with [9,11,17]. Region I includes the initial stiffness drop, while Region II relates to the period over which the stiffness remains level. Region III leads up to final degradation and the ensuing failure. The curve has been piecewise smoothened with a 4th degree polynomial to filter out the heavy load cell related noise in the stiffness calculations. The co-ordinate system for the sample specimen as: x in width, y in thickness and z in axial length.

As mentioned, the test was interrupted at 3 points (for XCT acquisition) in the loading timeline, at points 1A and 2A and 3A. There is a slight decrease in the modulus after reinstating the test after scans 1 and 2 marked by points 1B and 2B. This behavior has been observed previously [9] and can be attributed to the re-calibration and the sensitivity of the extensometer between the interrupted steps. There is no strong reason to believe that the low level of x-rays exposure degrades the mechanical properties of the composite, in fact x-ray exposure has been found to increase the matrix stiffness elsewhere [18].
Figure 3. Stiffness degradation curve during fatigue cycling with points demarcating interruption for characterization. Region I and III show steady falls in stiffness, while the stiffness is stable during region II. Nf=120,000 cycles

From the DIC maps in Fig. 4 we can clearly see hotspot regions that experience higher strain than the maximum gross strain of 1% imparted on the gauge. This is attributed to the presence of the 90° backing bundles running across the material, as can be confirmed in the CT volumes. At hotspots, the strain is as high as 2% which is very close to the tensile failure strain of the plate (2.25%), individual fibres (2.7%) and the matrix (4%). The regions at the periphery, have been masked out for DIC analysis because they go in and out of the field of view invalidating DIC analysis. The linear hotspots in strain (marked by rectangles in Fig. 4) correspond to the location of the backing bundles, while the point hotspots (marked by purple arrows in Fig. 4) are regions of crossover where the difference in waviness between UD and matrix is higher, which leads to coupled regions of higher and lower compliance.

Not only do the backing bundles perturb the ‘homogeneity’ of the microstructure, they also cause the UD bundles to be slightly wavy in the regions of the crossover, which leads to bending and a change in local orientation. This may be why some of the glass fibres fracture locally giving rise to other mixed mode damage modes of debonding, matrix cracking and transverse and longitudinal cracks.

As witnessed previously [9], the damage starts predominantly near the region of crossover between the UD bundles and the backing bundles, although in the previous work it was difficult to resolve any matrix cracks due to reasons of scale and resolution. The mixed mode damage propagation is mostly localized in clusters as seen in Fig. 5. Individual fibre breaks such as that seen in Fig. 6 and the associated debonding changes the local stress state leading to strain concentrations and breaks in neighbouring fibres, as discussed elsewhere [19].
Figure 4. DIC maps (between images at 0% strain and peak strain of 1%) showing hotspots in strain broadly correlated with the location of the backing bundles in the XCT volume render. The blue square near the top of the XCT volume shows the region of interest for corresponding XCT scans. The two pair of black bands on each map are O-rings from the extensometer. It should be noted that the alignment of the 90° bundles (red, blue, yellow and orange) are not precisely correlated with the hotspots, because the backing bundles in the bulk (not shown here) are not at the same z position as the ones on the surface shown here. The black box highlights regions which did not correlate correctly due edge effects.

Figure 5. A virtual YZ section taken from the region of interest CT at different stages in the fatigue cycling showing a localized damage cluster (boxed) involving matrix cracking and debonding, located in proximity to the backing bundles.
The x-ray CT scans do not appear to show clear evidence of classical progressive damage; instead, damage clusters originated and progressed only after the third scan. This does not definitely rule out the presence of damage in the microstructure prior to the third scan, as the first cracks in the backing bundles have previously been observed after as little as 480 cycles [9]. Indeed it is highly likely that damage has occurred in other regions of the test-piece which were not CT scanned in accordance with the drop in stiffness, as has been found in a number of studies [3,8,9]. Despite this, lack of evidence for progressive damage accumulation a transverse-longitudinal (YZ) macro-crack (Fig. 7) already present in the apparently pristine sample did undergo progressive damage evolution, more so in terms of opening up the crack, combined with more matrix cracking at higher cycles. The width of the macro-crack appears to increase progressively, although there has been no significant progression observed in the length of the crack, which seems to be arrested from the first XCT scan. Although it is probably due to the machining of the specimens and/or manufacturing and/or the first cycle over which the DIC strain map was collected, it is noteworthy that it is arrested at the backing bundle.

Figure 6. Virtual ZX section for the 4 fatigue stages showing neighbouring fibre breaks (boxed) in regions of crossover between the UD bundle and the 90° backing bundles.

Figure 7. Virtual YX cross-section for the 4 fatigue stages showing longitudinal a macro-cracks running through the periphery of the scanned CT volume, progressively extending and opening throughout the fatigue regime but being arrested at the backing bundle (boxed).
4. Conclusions
This study has shown that the strain field that develops in UD composite during fatigue loading is affected by the presence of the backing bundles. By correlating the strain field maps as a function of the number of fatigue samples with ex situ x-ray CT imaging of the composite it was possible to correlate the resulting stress amplification with localized damage initiation and ultimately to damage propagation and final failure. Advantages of this correlative method include the ability to directly relate hotspots in strain concentration with the underlying microstructure as a function of fatigue life to study the progress of damage accumulation. In this case most of the damage was not observed until just prior to fatigue failure. Next steps of this work will be to focus on designing experimental workflows to follow damage evolution at the microscale and combine it with digital volume correlation (DVC) to study the stress amplification in 3D.

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