

# Assessing the damage evolution of composites containing embedded fibre optics

In the work presented in this article, the non-destructive technique known as micro-computed tomography (micro-CT) was used to investigate the internal state of composite laminates containing embedded fibre optics. The laminates were subjected to cyclic loading and the damage was followed up in order to determine if the sensors affected composite lifetime. The experiments showed no significant evidence of damage related to the sensor's presence.

fecting structural integrity [1]. It is widely documented that by altering the microstructure of a composite layup, a stress redistribution takes place, which can potentially induce premature damage even for applied loads lower than the design loads [2]. Therefore, a better understanding of the problem is necessary in order to properly integrate fibre optic sensors into composite structures. In this work, optical fibre sensors of different diameters [3] were embedded in a carbon fibre prepreg UD material.

Samples were cut from the manufactured laminate and fatigue loads were applied up to failure. Damage evolution was monitored by means of a relatively new technique known as micro-computed tomography (micro-CT). This non-destructive inspection technology uses X-rays to investigate the internal microstructural state of any material with high resolution (2 µm). A damage assessment was performed after laminate production in order to investigate the influence of residual stresses on the optical fibre sensor surroundings. Furthermore, a specific load setup was chosen to fatigue the produced samples and the evolution of cracks was evaluated at intermediate steps using micro-CT.

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The use of optical fibre sensors (OFS) in the composite industry for research purposes, and for structural health monitoring (SHM) applications, has increased over the last decade. This has stimulated the demand for more specific applications, driven the development of new sensors and introduced new challenges, such as the integration of optical fibre sensors in composite materials without significantly af-

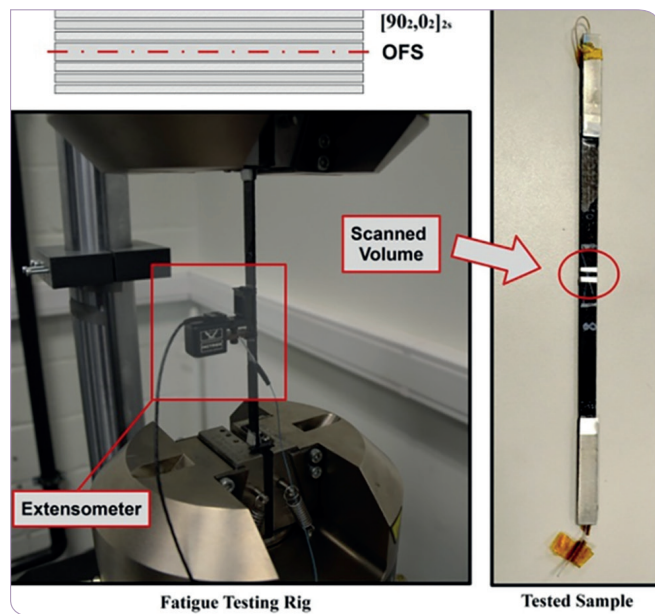


Fig. 1: Fatigue testing set-up with detail of the sample geometry and lay-up; the scanned region is highlighted in red on the sample

In summary, this work aims to address questions related to the composite/sensor interaction in long-term use, while strengthening the use of micro-CT technology for non-destructive inspections of composite materials.

## Materials and method

A carbon fibre epoxy prepreg (M55J-M18 from Hexcel)-based cross-ply laminate with a  $[90_2/0_2]_{2s}$  lay-up was manufactured by autoclave, using a 2-hour curing temperature of 180°C, a vacuum level of -80 kPa and an external pressure of 7 bar. In the mid-layer of the laminate, optical fibre sensors (OFS) with different diameters were embedded in alignment with the reinforcing fibres ( $0^\circ$  layers). A total of 5 rectangular samples were cut from the laminate (dimensions  $t \times w \times l = 2 \text{ mm} \times 10 \text{ mm} \times 250 \text{ mm}$ ) and were tested under fatigue. Samples 1 and 2 had a 60/96  $\mu\text{m}$  cladding/coating diameter optical fibre, Sample 5 an 80/116  $\mu\text{m}$  cladding/coating diameter optical fibre, and Sample 8 an 80/190  $\mu\text{m}$  cladding/coating diameter optical fibre. Sample 9 had a 125/195  $\mu\text{m}$  cladding/coating diameter. All the fibres were coated with Ormocer (organic modified ceramic material) through a continuous process, best known as draw tower grating (DTG<sup>®</sup>) (see: [www.fbgs.com](http://www.fbgs.com)). The samples were loaded for fatigue testing for a predefined number of cycles. The fatigue test setup is depicted in Figure 1 (left). A tension-tension sinusoidal load cycle with a load ratio (R) of approximately 0.1 was chosen in order to avoid compression. To define the load limits, a preliminary set of tensile static tests was performed on 3 reference specimens, which were cut from the manufactured plate according to the dimensions provided in the ASTM D3039 standard. The average ultimate tensile stress (UTS) of the material was measured ( $830 \pm 40 \text{ MPa}$ ). The applied cyclic load was aligned with the fibre optic direction. The cycling frequency was set to 5 Hz. The stress varied sinusoidally between 50 and 450 MPa (~50% of the UTS) for 1,000 cycles. The sample was subsequently dismantled from the test bench and moved to the micro-CT facility for the scan.

The cycle was then resumed at the same stress level till 1,000,000 cycles. Since no evident damage was found after this last stage, the load amplitude was increased to 600 MPa (~70% of the expected UTS) and cycled for another 1,000 cycles, resulting in a total of 1,001,000 cycles. The following load cycles were continued at the same stress level till 2,000,000 cycles and, finally, till 4,000,000 cycles. Before and after each load cycle, a static test was performed to evaluate the stiffness degradation related to the damage state. The axial deformation of the sample during these tensile tests was measured in the central gauge length region using an extensometer.

To evaluate damage evolution inside the samples in the OFS surroundings, micro-CT scans were performed after each cycle sequence. The central zone circled in red in Figure 1 (right) represents the location where a micro-CT scan was taken.

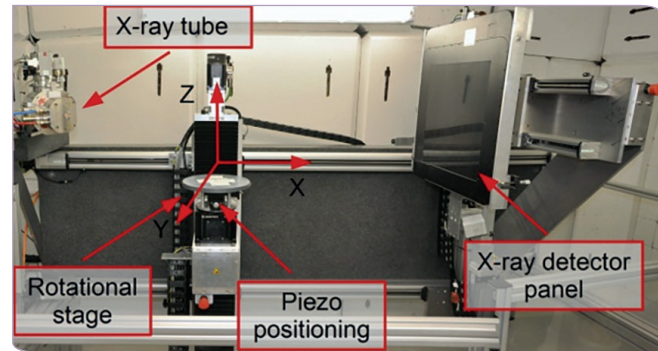


Fig. 2: Micro-computed tomography (micro-CT) scanner used for the nondestructive inspections

Aluminium tape stripes were used as a boundary to define the scanning region and were kept as a reference (to ensure the same region was scanned each time) on the samples during fatigue testing.

### Micro-CT setup

The scans were obtained using a modular 900-nm CT scanner [4]. A high-resolution micro-CT scanner optimized for research purposes is presented in Figure 2 as an example.

The sample was placed on a high-precision piezo-positioning manipulator and rotated, in order to obtain projections at different orientations. The X-ray tube, with medium (160 keV-150 W) to high energy (240 keV-280 W), directed its X-rays towards the sample at a minimum focal spot size of 2-4  $\mu\text{m}$ . The size and energy of the X-ray beam were crucial for reaching high-resolution CT quality. Far behind the sample, a flat detector panel acquired the outgoing rays on a relatively large area (20 x 25  $\text{cm}^2$ ). The scanner was equipped with up to 9 motorized axes, which allowed a large degree of freedom and the possibility of using large, bulky samples. After a first set of trials, the X-ray source was selected at 100 kV and 3 watts of target power, resulting in a voxel pitch of 2  $\mu\text{m}$  (resolution of the cross-section images). In total, 1500 projections were recorded over 360° and the radiographs were reconstructed with the in-house developed Octopus software package. The reconstructed pictures were post-processed with MATLAB<sup>®</sup> and analysed, while 3D renderings were made with VGStudio Max<sup>®</sup> from the original reconstructed images.

## Experimental results

### Initial state after curing

The scans presented in this section were taken after laminate production and sample preparation, while no mechanical load was applied yet. Figure 3 (top) shows the result of a slice (cross-section) of the laminate, which was reconstructed from the radiographs taken at different orientations. The area corresponds approximately to a region of 4 x 2  $\text{mm}^2$ . One can distinguish between the  $0^\circ$  and the  $90^\circ$  oriented layers; every layer is composed of two plies about 100  $\mu\text{m}$  thick. The mid

Table 1: Number of cracks counted on a section passing along the axis of the OFS for a growing number of cycles

Sample	0 cycle	1000000 cycles	1001000 cycles	2000000 cycles	4000000 cycles
1	0	6	8	19	23
2	1	10	11	21	30
5	3	12	13	20	24
8	2	11	17	21	26
9	5	11	13	22	30

layer has four 0° plies and the optical fibre is embedded in the centre. The side contours are curved due to the limited detector screen area, while the upper and lower edges are the sample's top and bottom surface. One can observe a richer resin film at each 0/90 interface layer: a darker colour is the result of a lower X-ray attenuation, meaning a lower density, which corresponds to a resinricher area.

The enlargement of the sensor surroundings (Figure 3 bottom) already highlights damage around the optical fibre of Sample 8, which has an 80-µm fibre with a 190-µm thicker coating. A transverse crack starts from the sensor's coating towards the interface with the nearest 90° layers. Samples 1 and 5 show no crack, resulting in a better coating/composite, and coating/cladding, adhesion. A point of interest ensues from the plies redistribution around the sensor creating resinrich areas sideways and, at the same time, compacting the reinforcing fibres above and below the sensor. This may result in higher local fibre volume fractions. The resin-rich areas appear

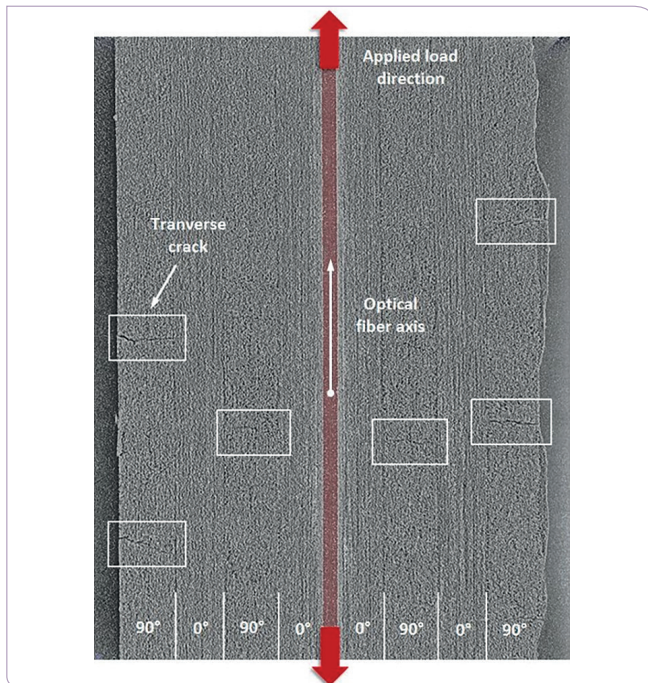


Fig. 4: Transverse cracks (confined in white boxes) evolving in the 90° plies due to fatigue cycling; the optical fibre is highlighted in red in the centre of the laminate

more marked for the smaller sensor, while the distortion of the plies around the fibre is less important.

### Damage evolution

After the initial scan, the laminates were tested for fatigue and scanned at defined intervals in order to investigate the overall damage evolution through the thickness. This was achieved by analysing the 3D rendered model of the scanned volume. As an example, Figure 4 depicts the number of cracks detected in Sample 1 after 1,000,000 cycles. Because of the cross-ply layup and the loading conditions, the cracks were expected to be initiated in the 90° layers perpendicular to the direction of the applied force [5].

To quantitatively evaluate damage through the thickness of the sample, the number of cracks arising in a cross-section along the optical fibre axis was tracked [2], [6]. For each sample, the number of cracks was compared at different number of cycles. Table 1 summarizes the overall number of transverse cracks counted.

An increase in the number of cracks in the 90° layers during fatigue testing is clearly noticeable. Besides this, however, no evolution of damage in the central 0° layers (interlaminar cracks) was yet found.

### Conclusion and outlook

Due to the high curing temperature (180°C) of the M55J-M18 carbon fibre prepreg, the thermal expansion coefficient difference between the hosting and the host materials was high enough to induce cracking in the area surrounding the fibre optic in Sample 8. In fact, in this case, the larger coating thickness, and its overall dimensions, distorted the composite architecture significantly more.

However, it is not yet clear whether the crack was initiated at the cladding/coating or at the coating/composite interface. When considering a smaller OFS diameter (80-µm fibre with thinner coating and 60-µm fibre), the arising thermal stresses were not sufficiently high to induce any damage. However, when analysing the 0° plies surrounding the OFS during fatigue cycling, no crack initiation was detectable after 4 million cycles. Also for Sample 8, which was already showing a crack, no further damage evolution was noticeable. Analysing the data contained in Table 2, the samples with a thicker fibre



embedded exhibit an overall crack number comparable to the smaller fibre samples.

Thus, it can be concluded that the sensor size does not adversely affect the overall lifetime of a carbon fibre cross-ply laminate subjected to tensile fatigue loading. ■

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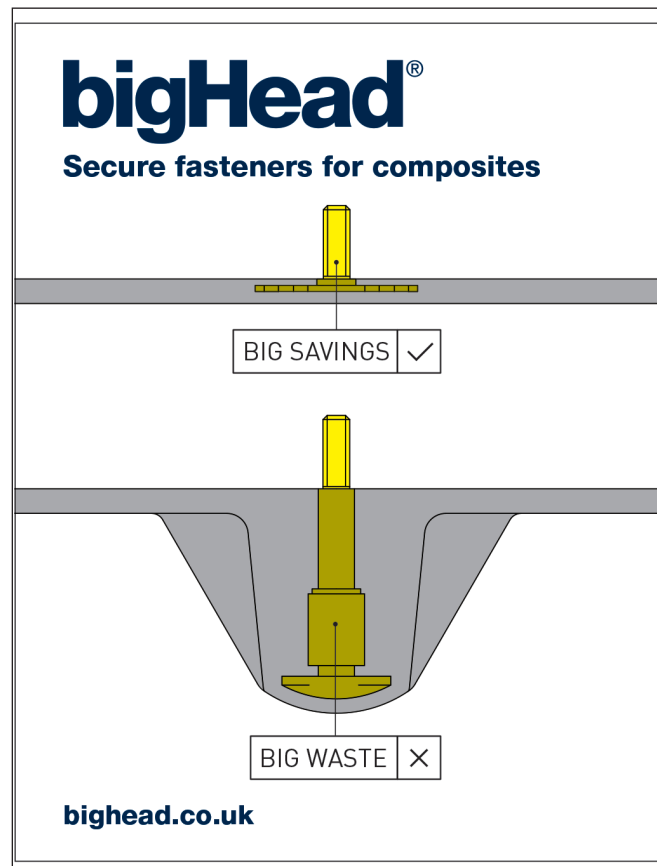
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