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► **To cite this version:**

Neha Chandarana, Sree Shankhachur Roy, Emmanuel Ramasso, Constantinos Soutis, Prasad Potluri, et al.. In-situ monitoring of braided composite tubes with optical fibres and piezoelectric sensors. International Conference on Composites Materials, Aug 2019, Melbourne, Australia. hal-03427058

HAL Id: hal-03427058

<https://hal.science/hal-03427058>

Submitted on 13 Dec 2023

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IN-SITU MONITORING OF BRAIDED COMPOSITE TUBES WITH OPTICAL FIBRES AND PIEZOELECTRIC SENSORS

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Keywords: Acoustic emission, Braiding, Clustering, Optical fibres, Structural health monitoring

ABSTRACT

In this work, damage monitoring is achieved by embedding a 10-metre long distributed optical fibre sensor (DOFS) between a thin shell composite tube and subsequent layers of over-braiding. The DOFS provides *in situ*, discrete strain measurements along its length, allowing full-field monitoring of the braiding, resin infusion, and curing processes. Piezoelectric wafer active sensors (PWAS) surface mounted on the cured composite tube facilitate acoustic emission (AE) monitoring during quasi-static flexural loading of the tube. The two sensing methods combined enable the early detection and recording of damage events in the tube, in real-time, while application of a clustering algorithm to AE data *a posteriori* shows potential in the classification of signals according to different damage mechanisms.

1 INTRODUCTION

The improvements in automation of the manufacture of composites have facilitated the increased use of near-net shape preforming processes. The quality of components is greatly improved, but so is the complexity of manufacture. Defects such as voids may go undetected, and act as failure initiation points when the component is subjected to in-service loading. Structural health monitoring (SHM) and non-destructive inspection (NDI) systems can be used to detect and monitor the growth of damage in-service, but cannot necessarily capture defects prior to loading. For this reason, the integration of sensors, which are also capable of monitoring the manufacturing process, and the resulting imperfections and induced stresses (residual), is particularly attractive.

The aim of this work was to instrument a composite tube such that defects and damage which arise during the manufacturing process and flexural loading can be detected, localised, and monitored. This is an extension of work presented on composite plates in an earlier study [1]. To achieve this, distributed optical fibres are embedded in the composite and used as *in situ* strain sensors, while piezoelectric sensors are attached (could also be embedded) to monitor acoustic emission activity during repeated flexural loading of the specimen.

2 MATERIALS AND METHODS

2.1 Manufacture of smart composite tube

The specimen studied in this work was manufactured in two phases. First, a thin shell tube was manufactured by wrapping two layers of a plain woven carbon fibre fabric (HTS-40 12k tows), pre-

impregnated with epoxy resin (TenCate TC250), around an aluminium mould of 50.8 mm outside diameter. The plies were arranged so that the fibre orientation was $\pm 45^\circ$ relative to the axis (0°) and hoop (90°) directions. The nominal thickness of each cured pre-preg layer is 0.25 mm. The shell, shown in Figure 1a, was cured in an autoclave. Following this, two layers of braid were constructed onto the cured composite tube, using T700SC carbon fibre tows (12k filaments). A $\pm 45^\circ$ braid was produced for both layers. The first layer of braiding applied over the pre-cured tube is shown in Figure 1b.

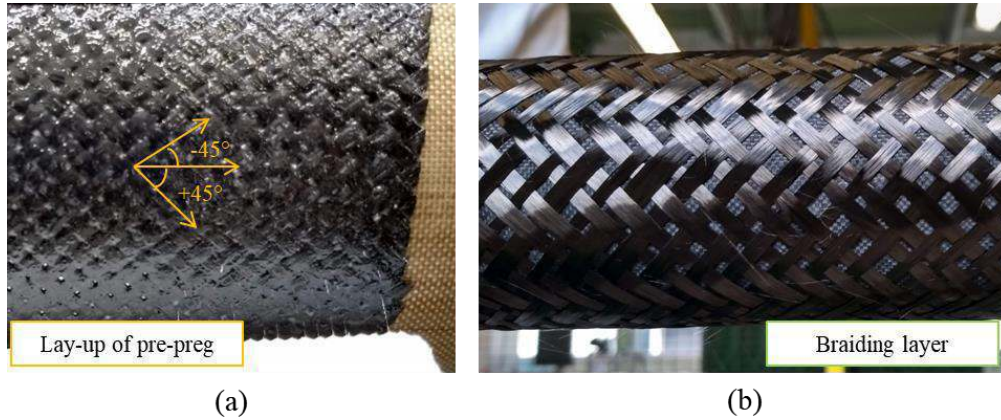


Figure 1. Manufacture of smart composite tube: (a) lay-up of pre-cured tube, (b) application of braid onto cured thin shell tube.

A 10-metre length distributed optical fibre sensor (DOFS), supplied by Luna Technologies Inc. was integrated between the two braided layers during both phases of the manufacturing process. Four sections, approximately 1 metre each in length were defined as OF regions 1-4, as per the schematic in Figure 2. Each optical fibre (OF) region is labelled, and the yellow circles show the approximate locations of small spots of cyanoacrylate adhesive which were used to hold the optical fibre in place prior to braiding. Embedding the sensor at this stage allowed for *in situ*, real time, distributed strain measurement during the second phase of manufacture, during lay-up, resin infusion, and curing. The use of K-type thermocouples and optical fibre temperature-compensation methods allowed separation of the mechanical strain from the thermal strain that developed during curing, enabling recording and analysis of curing-induced strains at different through-thickness levels.

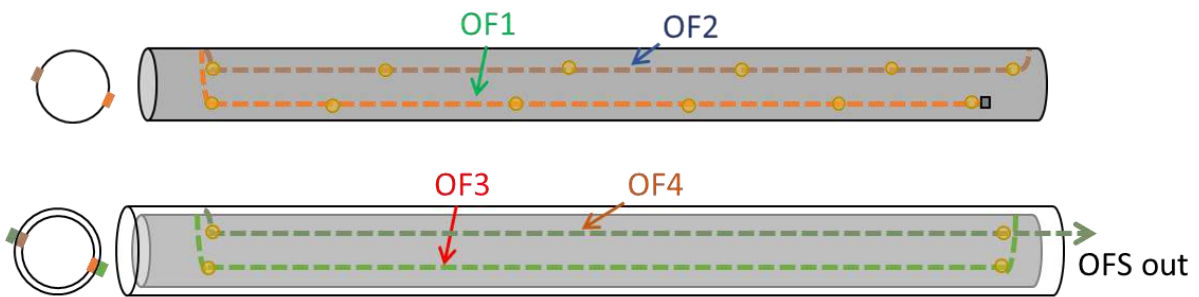


Figure 2. Position of optical fibre sensor embedded during the braiding process between the pre-cured woven tube and first braid layer (top), and between the two layers of braiding (bottom).

2.2 Flexural loading experiment

After curing, the 1.4 mm thick tube was trimmed to give a final length of 1.1 m. Then, eight piezoelectric wafer active sensors (PWAS), supplied by PI Ceramic, were surface mounted using a cyanoacrylate adhesive after preparation of the surface with grit paper. The tube was subjected to multiple quasi-static loading/unloading cycles in a three point bending configuration, on an Instron

testing machine equipped with a 50 kN load cell. The maximum load was increased incrementally to encourage the progression of damage in the tube. The loading set-up is shown in Figure 3. Curved aluminium supports with rubber pads were placed between the specimen and the machine's loading points enabling even distribution of the load around the circumference of the tube.

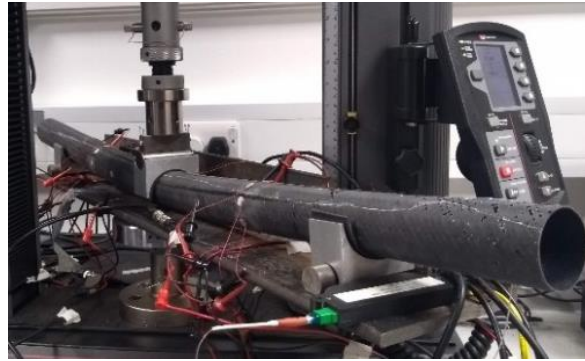


Figure 3. Quasi-static three-point loading of the composite tube.

During loading, AE activity was recorded via eight channels on a PCI-2 based acquisition system supplied by Mistras. Discrete AE waveforms (hits) were recorded using the 'AEwin' software package. The threshold amplitude was set to 55 dB to eliminate sources of extraneous noise, and to account for the 20 dB of pre-amplifier gain per channel. The sampling rate was set at 10 MHz (5 MHz on 2 channels due to hardware limitation) and AE timing parameters set to the default values: peak definition time (PDT) = 200 μ s, hit definition time (HDT) = 800 μ s, hit lockout time (HLT) = 1 ms, maximum signal duration = 1000 ms.

3 RESULTS AND DISCUSSION

3.1 Strain monitoring during manufacture

The embedded distributed optical fibre was used to follow the development of local strains in the tube during resin infusion and curing. During resin infusion, the flow front of the resin can be tracked from discrete strain values obtained from different locations along the length of the DOFS. The change in strain in the four identified OF regions is shown in Figure 4. The x-axis represents the discrete strain sensors along the length of the optical fibre; the gauge length of each sensor is 1.25 mm. As braiding commences over the pre-cured tube, tensile strains develop on the surface, as seen in the strain profile. As braiding progresses, tensile strains begin to develop in both OF regions (either side of the loop region). The strain continues to increase until a peak is reached, visible at sensors 1200 and 2000 (along the x-axis). A probable cause for this steady increase in strain, and abrupt reduction after a peak is reached, is the presence of the small spots of cyanoacrylate adhesive applied before braiding.

3.2 Strain monitoring during loading

The strain in OF1 and OF2 regions was not possible to monitor since part of the optical fibre was damaged during the tube's trimming process to its final length. Hence, during mechanical loading, only the strain in OF3 and OF4 was monitored. In addition to the loss of sensitivity after the break, the loss of the metallic mirror at the end of the optical fibre meant that the intensity of the strain signal was significantly reduced towards this end of the fibre. This loss of sensitivity leads to the loss of some data when the optical fibre is strained. The development of strain in OF3 and OF4 during the first cycle of loading is shown in Figure 5. The damage profile is shown at different stages of the loading cycle, as per the legend to the right of the plots. The loss of strain data observed as loading progresses is most likely a result of the damage sustained during cutting of the cured composite tube, since the strain values

could be recorded when the load was removed from the specimen. There is clearly an effect on the reliability of strain data when the optical fibre becomes damaged, particularly in the length close to the damaged region.

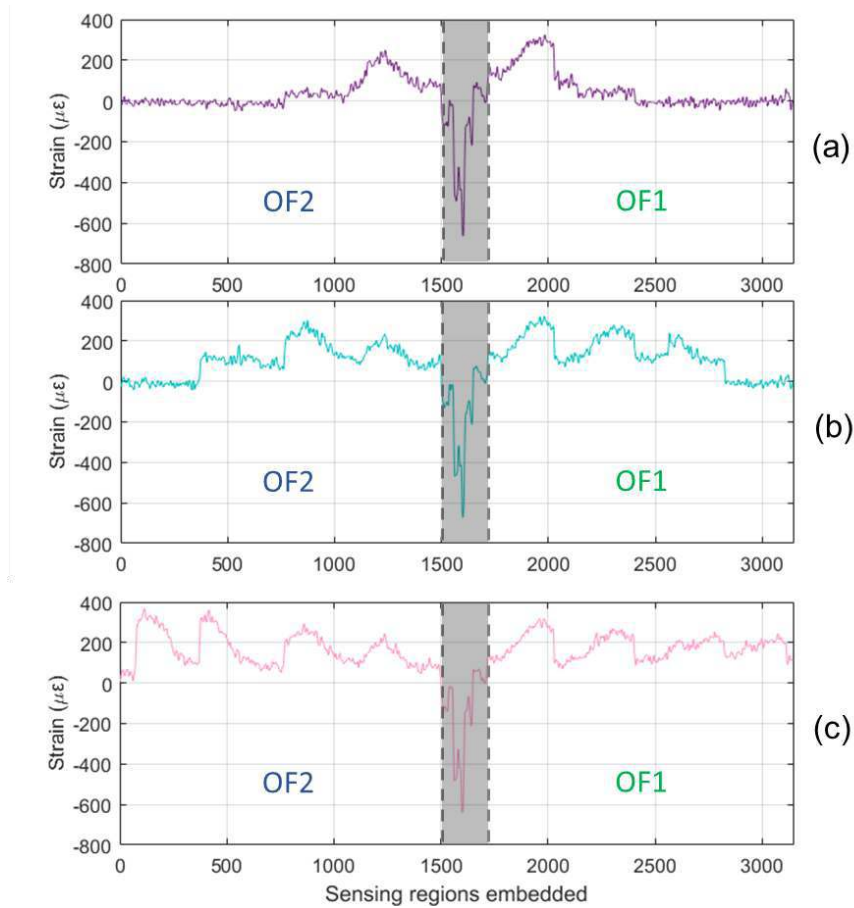


Figure 4. Development of axial strain in OF1 and OF2 during the application of the first layer of braiding. The loop region between OF1 and OF2 is greyed out as the strain values from this length are not utilised due to the curvature in the fibre. X-axis represents discrete sensors along the length of the optical fibre, spaced 1.25 mm apart.

3.3 Acoustic emission monitoring during loading

During each loading cycle, AE hits were recorded by all 8 PWAS. Using the AE time of arrival (ToA) method, and experimentally obtained wave velocities from the specimen, it was possible to obtain approximate co-ordinates for the location of damage sources during loading. A 2-D map of the calculated damage locations for the final loading cycle is shown in Figure 6. The presence of signals during earlier cycles of loading correlates well with the damage locations observed in the final cycle of loading, suggesting that it may be possible to estimate the failure location before reaching 70% of the breaking strength of the specimen. Most of the hits are happening in the middle section of the tube where maximum deflection and hence damage is expected to develop in the form of resin cracking, splitting and delamination before fibre fracture that would lead to ultimate failure of the tube.

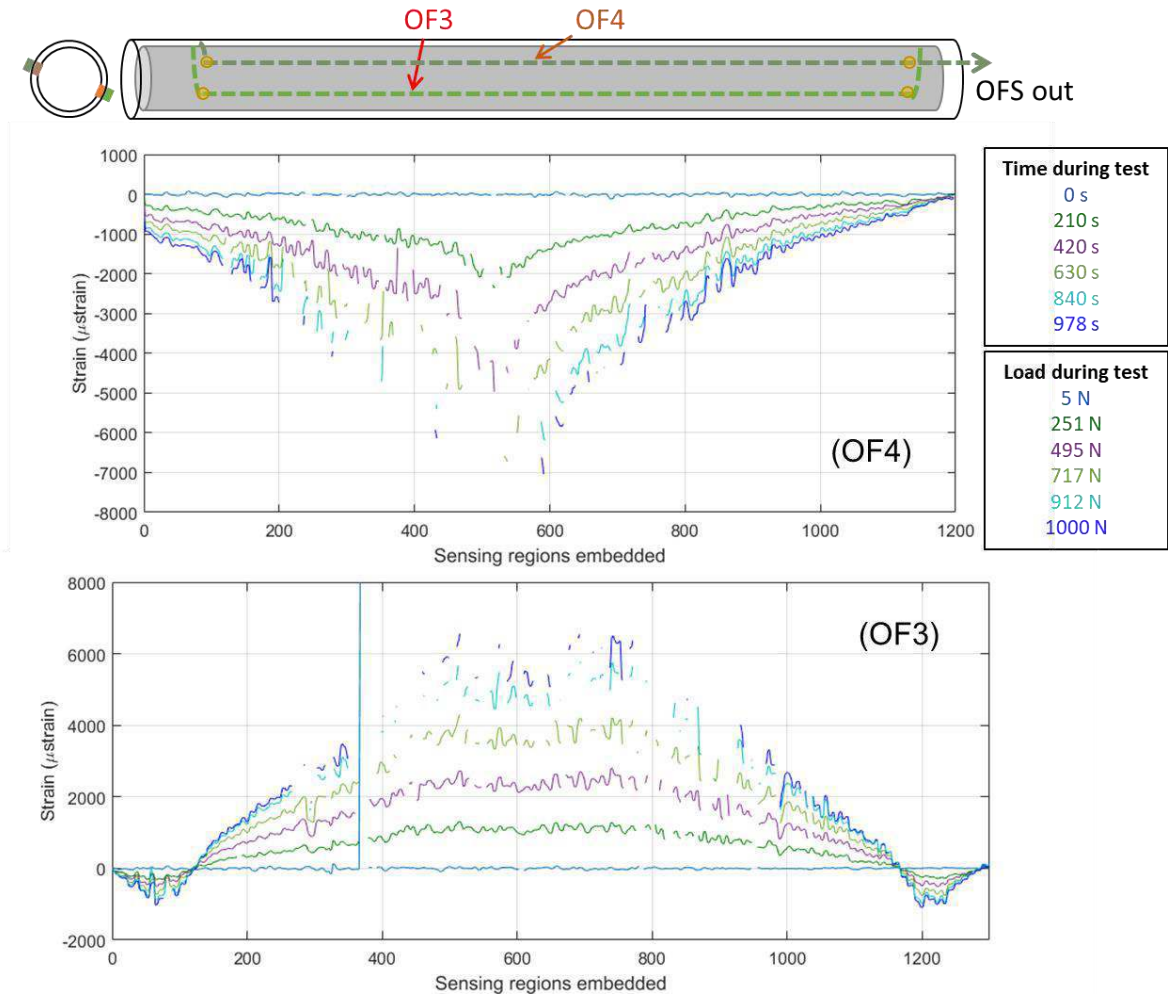


Figure 5. Development of strain in OF3 and OF4 during the first cycle of loading. X-axis represents discrete sensors along the length of the optical fibre, spaced 1.25 mm apart.

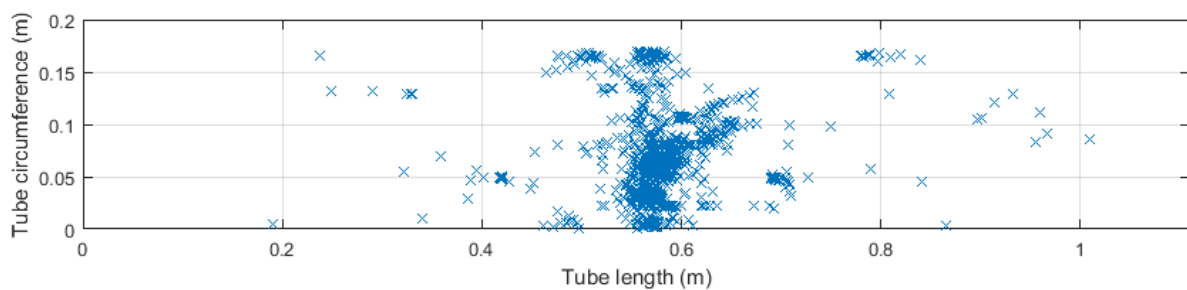


Figure 6. Estimated acoustic emission source locations for the final loading cycle (cycle 7).

3.4 Clustering of acoustic emission data

It is possible to infer possible damage modes – e.g. fibre fracture, matrix damage, interface failure, and delamination – using signal features such as amplitude, frequency, duration, and energy [1], [2]. As the number of data points is large, particularly for the later loading cycles, an unsupervised clustering method is applied to the data. The method (based on an earlier version presented in [3]) uses many AE signal features to separate data points into groups (clusters) to be able to classify different damage modes. Using subsets of 4 from a total of 17 features (as extracted through ‘AEwin’) per AE hit, an

unsupervised pattern recognition algorithm (based on the Gustafson-Kessel algorithm [4]) is applied to the full dataset for the specimen. The number of subsets which are taken into account to obtain a clustering result are selected based on their compliance with regards to a time-based criterion, which was not utilised in [3]. The algorithm is run multiple times to optimise the number of clusters. The optimum is found by maximizing the normalized mutual information criterion (NMI) [5].

Application of the clustering algorithm on AE hits from the specimen, when the 7 cycles of loading are combined, results in separation of the data into 18 clusters, based on the maximised median NMI. The initiation and evolution of signals within each cluster are shown in Figure 7. The envelope around each damage profile represents the uncertainty of the result for the evolution of that cluster. The uncertainty is much lower for the clusters that initiate in the earlier cycles of loading, and higher for the clusters that initiate later. Damage in composites can usually be decomposed into different phases throughout loading due to the cascading damage processes that occur during loading. Based on this, it is possible to develop a classification of damage types, for each cluster. It is argued that AE data belonging to cluster 1 are likely to arise due to friction between the specimen and test equipment: this cluster represents the largest group of data points, and data are acquired almost continuously during loading. Similarly, the data in clusters 2, 3, and do not result in a significant change in cumulated energy. They are, however, well separated in time, indicated that they represent different sources. AE data belonging to clusters 17 and 18 are more likely related to the final failure of the specimen: an abrupt increase in energy is observed, indicating high energy, catastrophic damage events during these last few seconds of loading. The clusters in between – clusters 5 to 16 – likely represent AE signals arising from damage progressing during loading, such as matrix cracking, fibre breakage, fibre pull-out, and delamination.

These clusters are difficult to separate temporally, indicating that these signals relate to damage progression. Taking into account the onset times and evolution of the clusters, the damage profiles can be decomposed into four temporal stages: (i) 0-2000 s: non-damage related signals and small matrix cracks which occur at the start of each loading cycle; (ii) 2000-6800 s: growth of matrix cracks into larger damage mechanisms including fibre buckling, interfacial debonding, and delamination; (iii) 6800-

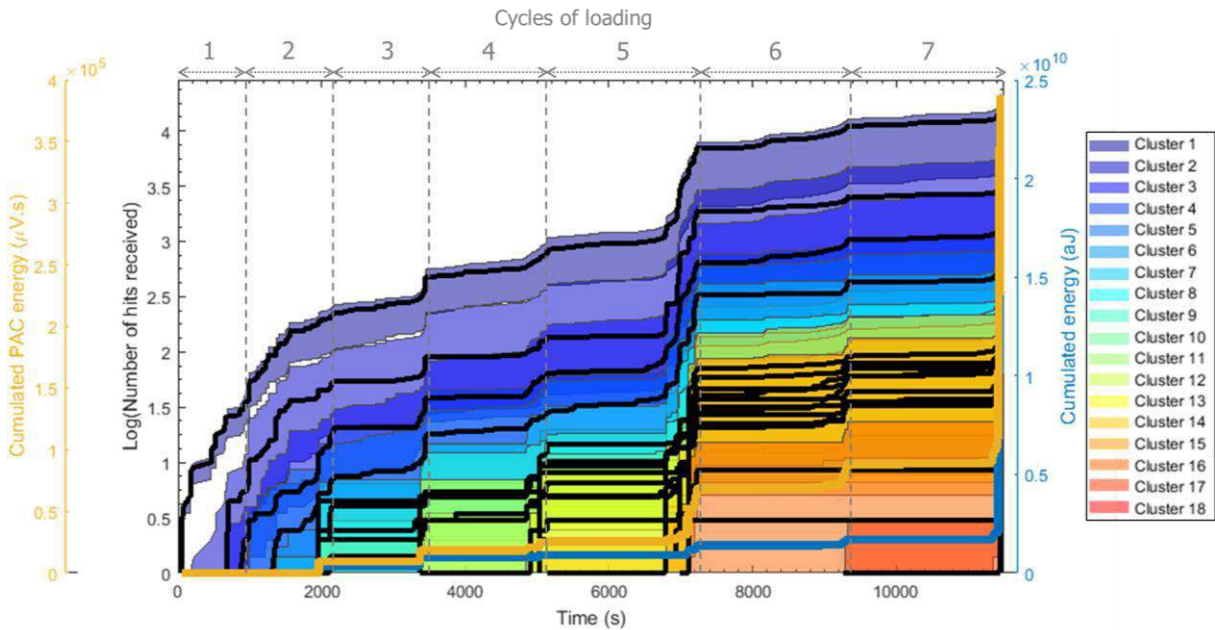


Figure 7. Damage profiles of each cluster for all cycles of flexural loading. Two different measures of cumulated AE energy are overlaid in blue and gold. Envelopes around the profile of each cluster relate to the uncertainty associated with the evolution of each cluster, coloured as per the legend to the right of the graph.

7200 s: significant growth of delamination, fibre pull-out and fibre breakage, indicated by a jump in the energy of recorded AE signals; and (iv) 7200-11200 s: growth of damage which initiated during loading cycles 3-5 with significantly higher energy – new clusters during this phase are likely representative of multi-modal damage leading to the ultimate failure of the specimen.

4 CONCLUDING REMARKS

In the present work, distributed optical fibres have been utilised to monitor the development of strain during manufacture and during loading. It is possible to observe strain even in the presence of damage to the optical fibre, however care should be taken to avoid damage as the reliability of strain data is affected significantly. The potential for the use of acoustic emission is demonstrated as a tool for detecting, localising, and classifying damage mechanisms arising during quasi-static loading. The use of an unsupervised clustering algorithm eliminates any operator bias and reduces the time taken to obtain a final result. Further work is required to develop an energy based criterion for linking data clusters to individual damage modes in the composite, validated by means of destructive and non-destructive techniques via, for example, x-ray computed tomography and ultrasonic C-scanning. Identifying the location, size and type of damage is of great importance in the effort to estimate analytically residual life and long term performance of the composite tube [6].

ACKNOWLEDGEMENTS

The authors acknowledge the funding and technical support from BP through the BP International Centre for Advanced Materials (BP-ICAM), financial support from EPSRC (EP/L01680X) through the Materials for Demanding Environments Centre for Doctoral Training, and funding and technical input to support the collaboration with The University of Manchester from the EIPHI Graduate School (contract “ANR-17-EURE-0002”) and FEMTO-ST Institute. This work has been partly done in the frame of the research project RESEM-COALESCENCE, managed by the Institut de Recherche Technologique Matériaux Métallurgie Procédés (IRT M2P) and financially supported by the French research program Plan d'Investissement d'Avenir (PIA). The use of manufacturing facilities and expertise from the Robotics & Textile Composites Group and Northwest Composites Centre is also gratefully acknowledged.

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