CRACK PROFILE RECONSTRUCTION OF CFRP-CFRP BONDED JOINTS FROM OPTICAL BACKSCATTER REFLECTOMETRY AND COMPARISON WITH X-RAY COMPUTED TOMOGRAPHY

Andrea GIANNEO¹, Michele CARBONI²*, Andrea BERNASCONI³

¹ Politecnico di Milano, Department of Mechanical Engineering
Via La Masa 1, 20156 Milano, Italy, andrea.gianneo@polimi.it

² Politecnico di Milano, Department of Mechanical Engineering
Via La Masa 1, 20156 Milano, Italy, michele.carboni@polimi.it – * Corresponding author

³ Politecnico di Milano, Department of Mechanical Engineering
Via La Masa 1, 20156 Milano, Italy, andrea.bernasconi@polimi.it

ABSTRACT

Adhesive bonding is one of the most suitable joining technique for composite lightweight structures, allowing lower stress concentration in the substrates, thus reducing the dimensions and the weight of connections. In adhesive joints, the Back Face strain method is often used as an effective SHM technique, where, dealing with single lap joints, the BF strain displays a characteristic negative peak caused by the rotation of the joint whose position varies if a crack is propagating within the adhesive. In this work, the Optical Backscatter Reflectometry (OBR), i.e. a distributed sensing technique, is used to monitor fatigue crack growth damage of woven CFRP-CFRP single lap bonded joints. Crack profile reconstructions from the BF strain peak profile recorded by distributed fiber sensing technology are here reported and referenced with X-Ray CT reconstructions.

Key words: Non Destructive Testing, X-Ray Computed Tomography, Optical Backscatter Reflectometry, Single Lap Joints, Carbon Fiber Reinforced Composites

1. Introduction

The use of adhesives has increased significantly in recent years in a range of industrial applications (e.g. civil [1], automotive [2], aerospace [3], railway field [4]). In spite of the well recognized advantages of this joining technique [5], particularly for composite structures, lifetime prediction of bonded joints is one of the most significant factors restricting the use of adhesive technology [6]. In particular, it remains considerable uncertainty in predicting joint lifetime due to [7–14]: environmental conditions (temperature, moisture), load types (static, fatigue), adhesive properties, spacers (wires, spheres, …), ageing effects, etc.
Proper non-destructive testing (NDT) and structural health monitoring (SHM) techniques are required to assess the state of joints, particularly in the case of fatigue loading. Nowadays, the applied SHM techniques are, in general, based on different physical phenomena [15]: dynamic modal data, electromechanical impedance, static parameters (displacement field, strain gauges, optical fibers etc.), acoustic emission (AE) and elastic waves.

Applying a continuous monitoring system makes possible to evaluate the development of damages in real time. From this point of view, as shown within the aeronautical field [16], switching to a condition-based maintenance can improve the safety and, at the same time, minimize costs with respect to scheduled inspections than common inspection procedures based on the “Damage Tolerance” approach, according to which a structure must be stopped and checked at least two times before possible failure can occur, with consequent inconveniences in terms of both down-time and money. The present research concentrates on the exploitation of the Back Face (BF) strain technique [17] as a SHM for bonded joints and it is an evolution of the works already published in [18–20]. By the BF strain method, strain sensors are placed on the two faces of adhesively bonded Single Lap Joints (SLJs) and one possible solution is the adoption of arrays of sensors.

Differently to FBG (Fiber Bragg Grating) [21] and CFBG (Chirped Fiber Bragg Grating) [22] sensors, the Optical Backscatter Reflectometry (OBR) technique utilizes swept-wavelength interferometry (SWI) [23] to interrogate optical fibers, allowing strain measurement along an entire single fiber with thousands of sensing locations interrogated simultaneously, transforming an ordinary optical fiber into a high spatial-resolution strain sensor. In order to demonstrate the opportunity of exploiting the BF strain monitoring technique of an OBR distributed sensing to monitor Fatigue Crack Growth (FCG) in bonded joints, a validation by other techniques was proposed in a former work [19], where results were compared to a linear Phased Array Ultrasonic Testing (PAUT) technique and showed an overall fairly good agreement. Anyway, the former research previously pointed out that the involved failure mechanisms are quite complex since they are the superposition of cohesive, adhesive and delamination damages.

Hence, with the aim of achieving a deeper insight, this paper investigates the feasibility of a Structural Health Monitoring system based on distributed sensing by Optical Backscatter Reflectometry (OBR) comparing the results to those from a volumetric NDT inspection like X-Ray Computed Tomography.

2. Experimental Setup

The adopted specimen is representative of a low modulus CFRP-CFRP single lap joint, whose stacking sequence is equal to [+45/0₂/+45]s and the thickness of each lamina is 0.66 mm, which makes the total thickness of each adherend equal to 5.3 mm. The adherends were bonded by epoxy structural adhesive Scotch Weld 9323 B/A with an overlap of 25.4 mm. A uniform adhesive thickness was guaranteed by 0.2 mm diameter glass spheres; the engineering constants of the here considered woven CFRP are reported in [19]. A fatigue test was carried out according to the experimental set-up showed in Fig.1 (a), using a uni-axial MTS 810 servo-hydraulic testing machine of 100 kN capacity. The cyclic load, chosen on the base of a previously obtained S-N curve of the joint, was characterized by an amplitude of 2.5 kN and a fatigue ratio R equal to 0.05.

One single low bending optical fiber, type “Strain sensor 2m” by Luna Innovations Inc., was bonded by means of a Z70 cyano-acrylate based rapid adhesive on the front and back surfaces of the specimen in the overlap region, as shown schematically with a dotted white box in Figure 1(a). The fiber was bent four times in order to obtain four measuring segments on the front (#1, #2, #3, #4) and back surfaces (#5, #6, #7, #8).
Moreover, with the aim of verifying damage occurred and reconstructed by the distributed sensing capabilities of OBR strain gauges, the same specimen was finally inspected by a volumetric NDT technique like X-Ray micro computed tomography as reported in Fig. 1 (b).

3. Structural health monitoring by optical strain gauges

An OBR interrogator, model ODiSI-B was used to measure the strain along the optical fiber. Thanks to OBR technology, the interrogation, hence strain measurement, is performed along the entire fiber with thousands of sensing locations interrogated simultaneously, transforming an ordinary optical fiber into a high spatial-resolution strain sensor. On the subject, strain values can be evaluated over discrete portions of the fiber, acting as virtual sensors defined as gauge length, which can be set by the operator in the OBR instrument. The adopted gauge length was 1.3 mm, with a gauge separation of 0.65 mm, see Fig. 2(a). Strain values were recorded every 75s during
the test and after each interruption. Moreover, the initial strain distribution was recorded to obtain a baseline from which damage evolution can be inferred. As already observed by the authors [19] in this un-cracked (“baseline”) configuration, the minimum strain peak is located at the end of the overlapping region, i.e. at 25.4 mm and it seemingly moves coherently with damage evolution across the overlapping region. For brevity, Fig. 2 (b) reports the baseline strain profile and the one after 320,000 fatigue cycles. A shift of the peaks is clearly highlighted with respect to those corresponding to the baseline condition, hence by simply taking the difference of the two status, damage extension can be evaluated along the overlapping regions, Table 1.

Table 1: Estimated damage according to OBR strain profile reconstruction after 320,000 cycles.

<table>
<thead>
<tr>
<th>Fiber Path</th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
<th>#4</th>
<th>#5</th>
<th>#6</th>
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</thead>
<tbody>
<tr>
<td>Peak Shift [mm]</td>
<td>3.3</td>
<td>4.6</td>
<td>6.5</td>
<td>5.2</td>
<td>6.5</td>
<td>7.2</td>
<td>9.8</td>
<td>7.8</td>
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<tr>
<td>Average Peak Shift [mm]</td>
<td>6.4</td>
<td></td>
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4. X-Ray micro computed tomography inspection

To corroborate the aforementioned estimated damage extension an X-Ray μ-CT NDT inspection was performed using a North Star Imaging X25 system. The adopted X-Ray source parameters were 76 kV and 40 μA, leading to a focal spot size of 3 μm, and a magnification of 4x (FDD=740mm, FOD=187mm); a number of projections equal to 1200 were acquired during a full rotation of the specimen. Moreover, the specimen was subjected to infiltration by a specially prepared liquid to enhance the image contrast (“enhanced X-Ray radiography”). Examples of CT reconstructions (3D voxel reconstruction) are reported in Fig. 3 and Fig.4. Fig. 3(a) shows the ROI (region of interest), whereas in (b)-(d) the damage extension and the failure modes after 320,000 fatigue cycles are reported along three orthogonal cutting planes (green=front side,
yellow=lateral side, red=downward planes). It’s worth noting that damage is not characterized/dominated by a single failure mode, but both adhesive and adherends are simultaneously involved.

Fig. 3: µCT volumetric reconstruction after 320,000 fatigue cycles: (a) Region of Interest, (b)-(d) slices according to three cutting planes.

By means of a cutting plane parallel to SLJ side (yellow one), see Fig. 4 (a)-(e), the damage extension and failure modes under optical sensing paths (#1-#8) can be highlighted and consequently measured as reported in Tab.2. Results are compared in Fig. 5 with those from OBR peak shift assessment. A fairly good agreement can be found between OBR and X-Ray CT both qualitatively regarding the trend, and quantitatively regarding damage extension under fiber paths, justifying the adoption of the peak shift as a method of measurement of damage extension under the sensing fiber path; the maximum error is equal to 1.4 mm for fiber path #1, #4 and #6. This value is of the same order of a volumetric NDT manual inspection system like ultrasonic Phased Array. Nevertheless, having a look to the estimated average damage extension, results
differ of 0.5 millimeters (lower value for OBR). This can be explained by the fact that the optical strain gauges are characterized by a measuring grid equal to 1.3 mm and are equally spaced of 0.64 mm, hence the spatial resolution of the system is limited to 0.64 mm.

Fig. 4: (a) Region of Interest,-X-Ray CT damage extension under (b) #3-#8, (c) #1-#6, (d) #2-#5, (e) #4-#7 fiber paths

Tab. 2: Estimated damage according to X-Ray Computed Tomography under fiber position

<table>
<thead>
<tr>
<th>Fiber Path</th>
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<th>#4</th>
<th>#5</th>
<th>#6</th>
<th>#7</th>
<th>#8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Damage Extension [mm]</td>
<td>2.3</td>
<td>5.9</td>
<td>6.9</td>
<td>6.6</td>
<td>7.7</td>
<td>8.7</td>
<td>9.8</td>
<td>7.0</td>
</tr>
<tr>
<td>Average Damage extension [mm]</td>
<td>6.9</td>
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5. Conclusions

The usage of optical fibers to monitor fatigue crack propagation in an adhesively bonded woven CFRP composite joint was highlighted. The full strain profile presents a minimum strain peak and the proposed monitoring techniques is based on the identification of its position with damage evolution. Based on the results presented the OBR technology allows for measuring the back-face strain profile in single lap joints and the intrinsic distributed sensing capabilities allowed for measuring the position of the minimum strain peak with a fairly good accuracy with respect to the damage quantified by a volumetric NDT technique as X-Ray μ-CT. Results have to be considered preliminary, particularly because they are based on one single test and need to be replicated with an extended number of samples under different fatigue loading conditions to be more representative.

6. Acknowledgements

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7. References


[8] Ferreira JAM, Reis PN, Costa JDM, Richardson MOW. Fatigue behaviour of composite adhesive lap joints n.d.


