EXPERIMENTS ON DISTRIBUTED FIBER OPTIC SENSING FOR FATIGUE CRACK GROWTH MONITORING OF COMPOSITE ADHESIVELY BONDED SINGLE LAP JOINTS

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Abstract

In this work, the Optical Backscatter Reflectometry (OBR) distributed sensing technique is used to monitor fatigue crack growth in composite, single lap adhesive bonded joints subject to constant amplitude (CA) fatigue loading. OBR allows for measuring the strain along the entire fibre with numerous, distributed sensing locations interrogated simultaneously, transforming an ordinary optical fibre into a high spatial-resolution strain sensor. Particularly, the structural health monitoring (SHM) approach exploited in this research work is the Back Face (BF) strain technique. The BF strain along the overlap is characterized by a negative peak, whose position varies if a crack propagates in the adhesive. This constitutes the basis for a structural health monitoring method, whose results in this paper are referenced with measurements by phased array ultrasonic testing.

1. Introduction

In adhesive joints, the Back Face (BF) strain method is often used for monitoring the structural integrity [1, 2] during service. In single lap joints, the BF strain along the overlap region displays a characteristic negative peak, caused by the rotation of the joint (Fig.1). As cracks/delaminations develop within the adhesive layer or between the adjacent laminae of the composite laminate substrates, this peak moves (see red circles in Fig.1). Previous studies demonstrated that a linear correlation exists between the position of the negative strain peak and the crack tip and this relationship was exploited for fatigue crack monitoring [3, 4].

To extract BF strain values, an array of sensors can be used, like standard electric strain gauges [4] or Fibre Bragg Gratings [3-5]. FBGs are often used for monitoring the integrity of adhesive joints or composites, thanks to the possibility of embedding them into composite laminates or in the glue line [6-9]. Recent developments of distributed sensing techniques, like Optical Backscatter Reflectometry (OBR) [10-12], made it possible to improve the spatial resolution of strain measurements, as shown in [13]. By OBR, strain measurements can be performed along the entire fibre with thousands of sensing locations simultaneously interrogated, transforming an ordinary optical fibre into a high spatial-resolution strain sensor.

In [14], some of the authors of this work used a standard optical fibre to measure BF strains by OBR in composite bonded joints. By analyzing the evolution of the BF strain, crack length was inferred based on the linear relationship between the position of the negative strain peak and that of the crack tip. Finally, results are compared to Phased Array Ultrasound Testing (PAUT) acquisitions, which is

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an advanced UT technique where an array of piezoelectric elements is electronically controlled in order to acquire easily cross-sectional views (L-Scan) of the inspected sample.

In this work, results of another fatigue test, conducted at a different load level than that applied to the specimen described in [14], is presented.

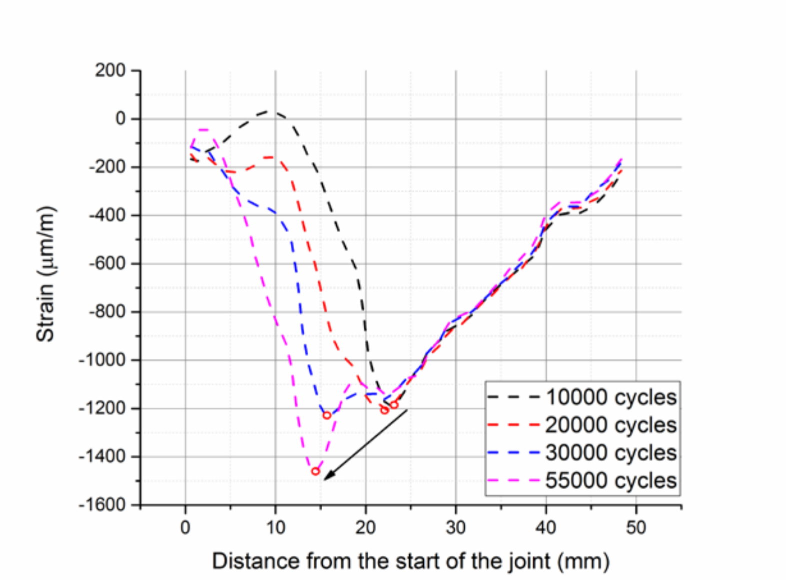

Figure 1. Typical BF strain paths of a single lap joint for different crack length (cracks in the adhesive)

2. Experimental setup

The specimen is a single lap adhesively bonded joint with CFRP adherends, see Fig.2. Both adherends are woven CFRP laminate. The adherends were bonded by epoxy structural adhesive Scotch Weld 9323 B/A (3M Company, St. Paul, MN, USA) with an overlap of 25.4 mm; more details about the specimen can be found in [14].

One single optical fibre (type "Strain sensor 1m", by Luna Innovations Inc., Roanoke, VA 24011, USA) was bonded on the top and bottom surface of the specimen in the overlap region, as shown schematically in Fig. 3, by means of a 2-component fast curing adhesive (X60). By bending the fibre, four measuring segments were obtained on one face, numbered 1, 3, 4 and 2, and other two segments, numbered 5 and 6, bonded on the other face. The latter fibre segments were bonded on the edges of the specimen, to leave accessibility and adequate coupling for the PAUT inspection, see Fig. 3.

Fatigue test were conducted in load control mode, using a uni-axial MTS 810 servo-hydraulic testing machine of 100 kN capacity. The cyclic load had 3.0 kN amplitude and the fatigue load ratio R was equal to 0.05. Test frequency was 10 Hz. The test was interrupted for strain, visual and PAUT measurements every 1,000 cycles up to 5,000 cycles, then every 10,000 cycles. All measurements were performed with an applied static load corresponding to mean value of the load cycle.

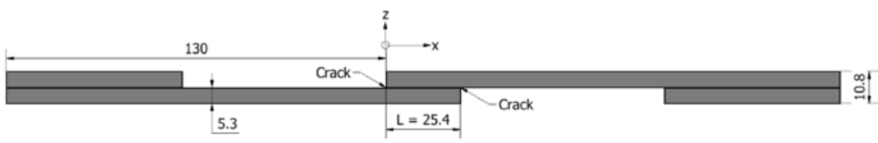

Figure 2. Specimen shape and dimensions

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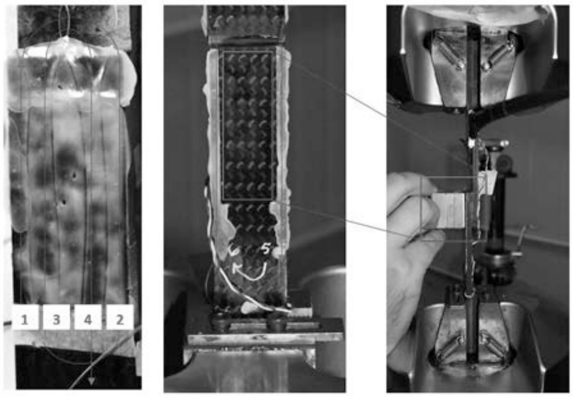

Figure 3. Position of the optical fibre segments used for strain measurements and PAUT probe.

2.1. Visual inspection

The position of crack tips appearing at the side surface of the joint was monitored by Visual Testing (VT) at the top and bottom ends of the single lap joint. Pictures of the cracks were taken using a Canon EOS 500D camera equipped by an optical stabilized 18-55 mm lens. Light source was a Bosch GLI DeciLed magnetic LED lamp. Crack length was measured by a post-processing image software as ImageJ [15].

2.2. OBR

For strain measurements, an ODiSI-B OBR interrogator by Luna Innovations Inc., Roanoke VA, USA was used. Strain values can be evaluated over discrete portions of the fibre, which acts as virtual sensors with a gauge length that can be set by the operator in the OBR instrument. A gauge length of 1.3 mm and a gauge separation of 0.65 mm were employed.

2.3. PAUT

PAUT Non Destructive Evaluations (NDE) were performed by means of an Harfang X-32 Phased Array unit, equipped with a 5 MHz 32 active elements linear probe. A “0° Linear-Scan” (L-Scan) was applied in order to inspect the cross-sectional central region of the sample. Eight active elements were sequentially activated, over the 32 elements full array, allowing for inspecting the whole bonded region without moving the probe.

3. Results and discussion

From the strain profile recorded by OBR equipment, the negative peak values were extracted and recorded at each test interruption. Based on the FE analyses reported in [5], linear relationships between the position of the negative strain peaks, measured from the nearest overlap end (L-$x_{\min}$) with reference to the coordinate system shown in Fig. 2, and the length a of the crack tip were found for strain values extracted along the centerline

$$L\text{-}x_{\min} = 0.900\, a\text{-}0.487 \tag{1}$$

and for values extracted along an edge path

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$$L\text{-}x_{\min} = 0.914\ a\text{-}0.141 \tag{2}$$

In both cases, a straight crack front was assumed.

By applying the corresponding relationship, the crack length was inferred from the position of the minimum strain peaks.

Two cracks propagated simultaneously from both ends of the overlap. Results for the lower and upper cracks are reported in Fig. 4 and in Fig. 5, respectively. In both charts, results from PAUT measurements of crack length are superimposed. It appears that, in the case of the lower crack, a good agreement exists between PAUT measurements and crack values inferred from OBR readings. Conversely, in the case of the upper crack, PAUT measurements are initially in agreement to OBR based crack length values, while, as the crack propagates, differences get more important, up to 3 mm.

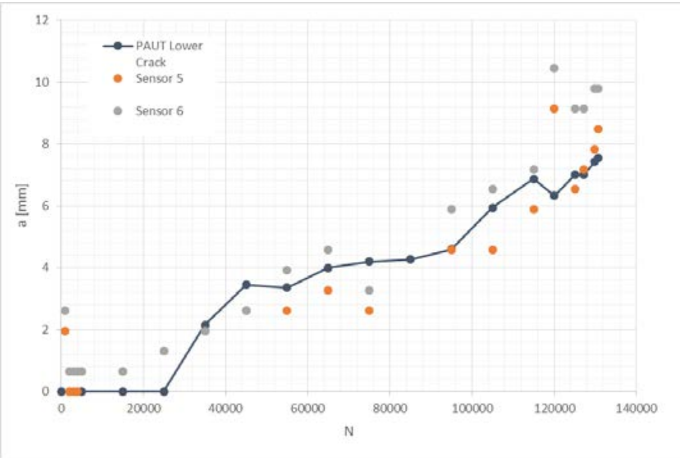

Figure 4. Lower crack length values as a function of the number of cycles, obtained by PAUT and OBR

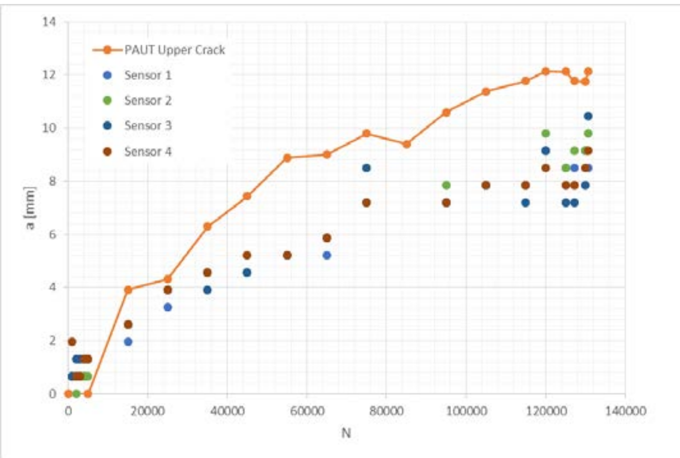

Figure 5. Upper crack length values as a function of the number of cycles, obtained by PAUT and OBR

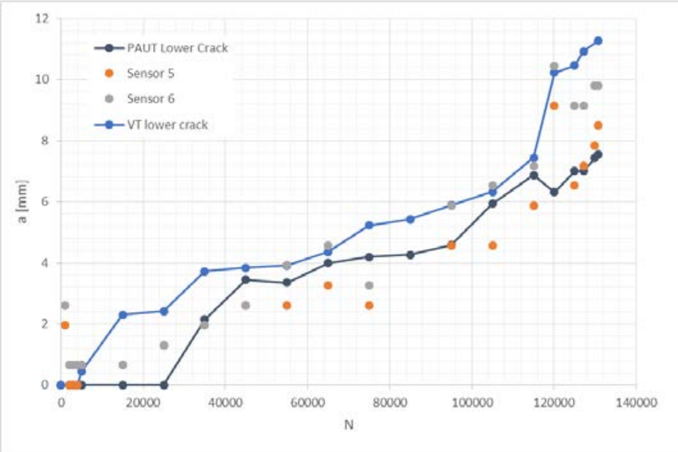

Figure 6. Lower crack length values as a function of the number of cycles, obtained by PAUT, OBR and VT

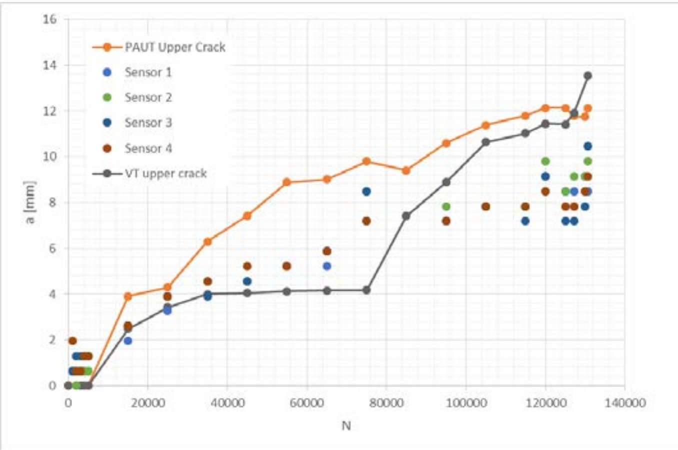

Figure 7. Upper crack length values as a function of the number of cycles, obtained by PAUT, OBR and VT

Values of crack length obtained by VT are superimposed to the correspondent graphs and plotted in Fig. 6 and 7, for the lower and the upper crack, respectively. It appears that VT, OBR and PAUT agree well in the case of the lower crack, whereas, in the case of the upper crack, VT agrees more with OBR than PAUT up to 95,000 cycles.

4. Conclusions

The results presented in this paper confirm that the BF method, combined with the high spatial resolution of strain measurements, by OBR technique, is a promising approach to the fatigue crack monitoring in bonded joints.

Values of crack length inferred from the position of the negative peak of the strain distribution along optical fibre segments bonded longitudinally on the back face of the specimen in the overlap region were in good agreement with visual inspections of the position of the crack front on the side of the specimen. Agreement with PAUT was good for one crack, whereas for the one propagating from the upper overlap end, differences as high as 3 mm were observed. It is worth noting that PAUT is capable

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to detect cracks as well as debonding in the composite layers underlying the adhesive. Therefore, further investigations are currently being conducted to achieve a better insight about the damage pattern by micro computed tomography.

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