

STRUCTURAL HEALTH MONITORING OF FATIGUE TESTED CFRP-CFRP BONDED JOINTS USING OPTICAL BACKSCATTER REFLECTOMETRY AND X-RAY MICRO COMPUTED TOMOGRAPHY

A. Bernasconi¹, M. Carboni^{1*}

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

Keywords: fiber optics, micro CT, composite adhesive joints, back face strain

Abstract

Nowadays, adhesive bonded joints find large application in modern structures, especially for their lighter weight, lower stress concentration and better fatigue properties. Anyway, issues might arise from a multitude of different factors, like manufacturing defects and operational condition, which lead to local debonding and final unpredictable failure. Consequently, structural health monitoring techniques, able to evaluate damage development in real time, and non-destructive testing are needed to assess the in-service state of the joints, particularly in the case of fatigue load conditions. In the present paper, a fatigue test is performed on a Carbon Fibre Reinforced Polymer single lap adhesive bonded joint, and its damage initiation and propagation are investigated using X-ray micro-Computed Tomography and the Back-Face strain technique performed applying a distributed optical fibre sensor implementing Optical Backscatter Reflectometry. A good linear correlation is found between crack depth measured by X-ray micro-Computed Tomography and the position of strain peaks recorded by Optical Backscatter Reflectometry.

1 Introduction

Adhesive bonding is often chosen for joints in composite structures. However, this choice calls for proper non-destructive testing (NDT) and structural health monitoring (SHM) techniques, particularly in the case of fatigue loading. The NDT and SHM techniques available for bonded joints include visual testing, ultrasonic testing, acoustic emission, ultrasonic guided waves and strain measurements [1].

The present work focuses on the Back Face (BF) strain technique and compares its performance to micro-CT. To apply the BF strain method [2]-[3], single strain sensors or an array of sensors are usually placed on the back face of adhesively bonded joints. For a Single Lap (SL) joint, Bernasconi et al. [4-5] used an array of Fibre Bragg Grating (FBG) sensors to monitor fatigue crack propagation. Similar experiments were performed by Canal et al. [6], Sans et al. [7], Stutz et al. [8] and Da Silva et al. [9].

Instead of an array of FBG sensors, Chirped Fibre Bragg Grating (CFBG) sensors can also be used (Sanderson et al. [10], Capell et al. [11] and Palaniappan et al. [12]). However, Optical Backscatter Reflectometry (OBR) technique, see Güemes et al. [13], allows for true distributed sensing of strain along an optical fibre (Frövel et al. [14] and by Grave et al. [15]). In [16], Bernasconi et al. measured the BF strain in a woven CFRP SL joint by OBR and a

single optical fibre. Experimental results showed that the OBR allows for high spatial accuracy in detecting the minimum peak of the BF strain profile. The position of this peak in a SL joint can be used to monitor the fatigue crack growth. This was shown by the authors of the present paper in [17], where the OBR technique was applied to fatigue crack growth monitoring in a CFRP SL joint and results compared with visual testing and Phased Array Ultrasonic Testing (PAUT).

The present paper presents the continuation of the work presented in [17], preliminary results of an experimental plan aiming at investigating the possibility of monitoring the structural health of adhesive joints by different methods. In this paper, the BF strain method by OBR distributed sensing is exploited to monitor FCG in the same SL composite joints as in [17]. Fatigue cracks were then analyzed by visual testing and micro CT, thus providing data to be compared with crack length values inferred from BF measurements.

2 Experimental

2.1 Material and specimen

The adopted specimen is a low modulus Carbon Fibre Reinforced Polymer (CFRP) single lap adhesive bonded joint. Particularly, both adherends of the joint are woven CFRP laminate with a stacking sequence equal to [+45/0₂/+45]_s. The thickness of each lamina is 0.66 mm, which makes the total thickness of each adherend equal to 5.3 mm. The adherends are bonded by an epoxy structural adhesive Scotch Weld 9323 B/A with an overlap of 25.4 mm (Fig. 1). A uniform adhesive thickness is guaranteed by 0.2 mm diameter glass spheres.

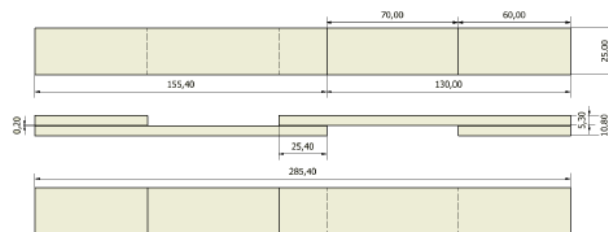


Figure 1. CFRP-CFRP single lap bonded joint.

2.2 Optical backscatter reflectometry setup

In order to carry out Optical Backscatter Reflectometry (OBR) strain measurements, the specimen was instrumented by a single low bending optical fibre, type “Strain sensor 2m” by Luna Innovations Inc., equipped with an LC/APC connector and a low reflection termination. It was connected to an OBR interrogator, model ODiSI-B by Luna Innovation Inc., and the control unit was connected to a PC, which elaborated data and enabled storage and visualization.

The optical fibre strain sensor was bonded, by a Z70 cyano-acrylate based rapid adhesive, on the top and the bottom surfaces of the specimen and along the overlap region (Fig. 2). As can be seen, the fibre is bent in order to obtain four measuring segments on both the front surface (numbered 1, 2, 3 and 4) and the back one (numbered 5, 6, 7 and 8) of the specimen. All Figures and tables must be inserted in the text with centered alignment. They should also be properly quoted in the text. All data should be given in SI units.

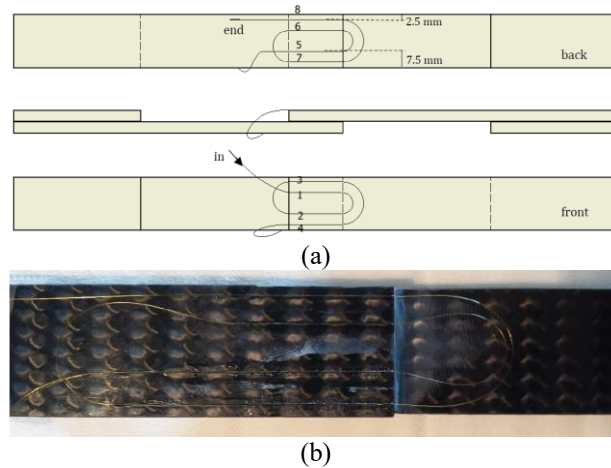


Figure 2. Application of the OBR sensor to the specimen.

Finally, the optical sensor was calibrated thanks to a mapping file univocally associated to the fibre and provided by the producer. This file contains the fingerprint of the considered optical fibre, which is the base for all kinds of measurements.

The optical sensor was, then, adopted, during the fatigue test, as a strain gauge able to measure the local strain of the component according to the BF strain approach (BF), whose main concept is shown in Figure 3.

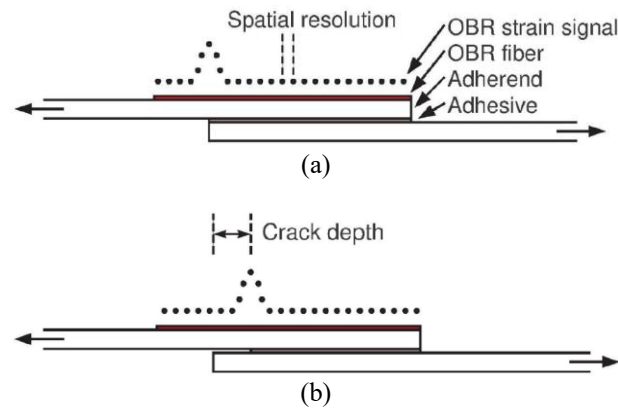


Figure 3. Back-Face technique: a) baseline measurement; b) shifting of the strain peak due to damage evolution.

Using OBR, the mean strain value can be evaluated over a discrete portion of the fibre which constitutes the virtual sensor and whose size can be chosen by the user. In this case, a gauge length of 1.28 mm with a gauge separation of 0.64 mm was adopted.

2.3 Visual Testing setup

Visual testing (VT) was carried out to evaluate the position and size of the outcropping crack tips at the top and bottom ends of the overlapped region. The set-up consisted of a high magnification Dino-Lite digital microscope supported by a gooseneck stand and a Bosch GLI DeciLed magnetic LED lamp used to light up the target surface (Fig. 4).

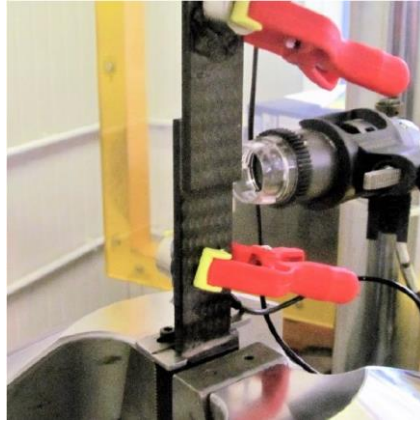


Figure 4. Visual testing set-up.

2.4 Micro-computed tomography set-up

The specimen was inspected through a volumetric NDT such as X-Ray micro computed tomography (μ -CT) performed by a North Star Imaging X25 μ -CT scanner (Fig. 5). X25 is a four-axis, digital radiography and computed tomography system designed for high-resolution imaging and measurement accuracy. It is equipped with a micro-focus X-RayWor XTC tube with a voltage range between 10 kV and 160 kV and a minimum focal spot size of 0.5 μ m. The detector is a flat panel X-Ray detector characterised by high sensitivity. It has a sensitive area of 145.4 \times 114.9 mm² and a pixel matrix of 1944 \times 1536 pixels.

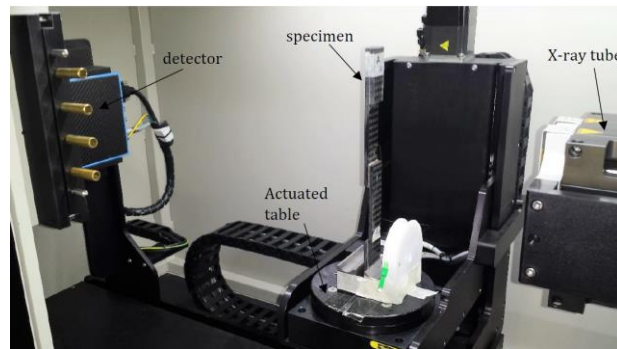


Figure 5. Micro-computed tomography set-up.

The parameters adopted to scan the specimen consisted in an x-ray source at 76 kV and 40 μ A, leading to a focal spot size of 3 μ m, and a magnification of 4x. The number of projections was equal to 1200 and they were acquired during a full rotation of the specimen. No filters were applied. To increase the image contrast of the damage with respect to the composite material and the adhesive, the specimen was subjected to infiltration by a contrast medium 1,4 Diiodobutane \geq 99% containing copper particles.

2.4 Fatigue tests

The described specimen was fatigue tested in load control mode 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, is characterized by an amplitude of 2.5 kN, a fatigue ratio R equal to 0.05 and a frequency of 5 Hz, so to ensure a test duration of, at least, 500.000 cycles. The test was interrupted twice, at about 320.000 cycles and about 465.000 cycles, in order to carry out inspections and data acquisitions, i.e. visual testing, a static acquisition of the strain by OBR and the volumetric inspection of the joint through μ -CT. All measurements were performed with the specimen subjected to the maximum load of the fatigue cycle.

3 Results

First, the Back-Face strain values of the initial condition were acquired along with the μ -CT scan and the pictures of the healthy joints. Afterwards, fatigue load cycles were applied to the above-mentioned test interruptions, at which all the measurements were performed again.

3.1 Optical backscatter reflectometry

The acquisition of the baseline strain distribution allows associating each BF peak to the corresponding measuring segment along the overlap (Fig. 6a). Moreover, the baseline acquisition allows deducing damage evolution with fatigue cycles. In particular, BF strain peaks shift coherently to crack evolution across the overlapping region and so it is possible to evaluate damage size by simply measuring the difference of the position of the strain peaks between the initial and actual condition. An example of the shifting of strain peaks between 0 and 320.000 cycles (first interruption) is reported in Figure 6b.

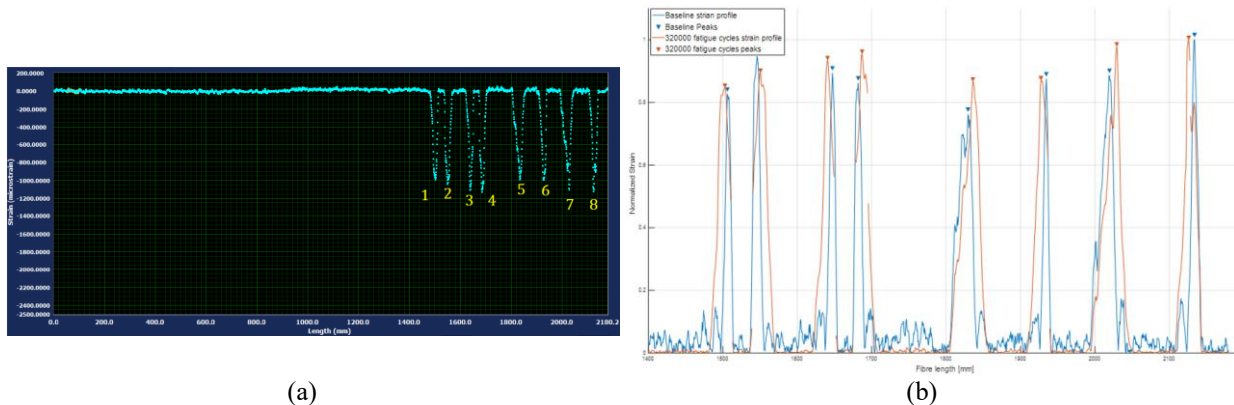


Figure 6. OBR measurements: a) baseline condition; b) evolution of strain peaks with fatigue damage (320.000 cycles).

3.2 Visual testing

Multiple acquisitions, generally four at each test interruption, were recorded. The four pictures depicted the overlap ends from all sides and tried to give a first feedback on the likely present damage. The acquired pictures were digitally elaborated, after a suitable calibration of the pixel-length relationship, to size the evolution of the emerging damage and to allow a comparison with the other methods. The example of the condition of the specimen at 320.000 fatigue cycles is reported in Figure 7.

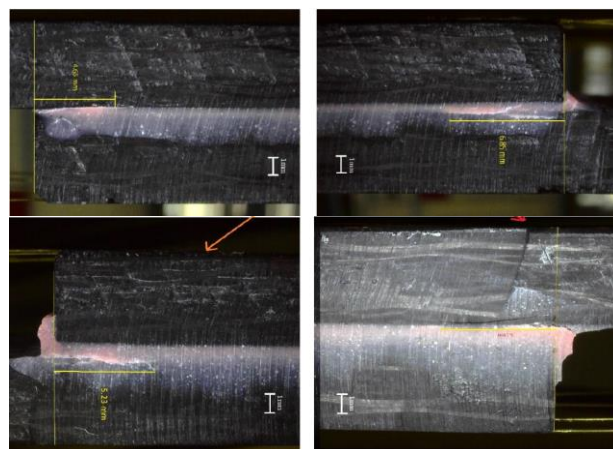


Figure 7. Visual testing acquisitions at 320.000 fatigue cycles.

3.3 Micro-computed tomography

The 3D voxel reconstruction of the overlapped region of interest of the specimen is shown in Figure 8. While visual inspection gives information on the visible damage, μ -CT allows studying the development of the damage three-dimensionally and through the thickness of the specimen.

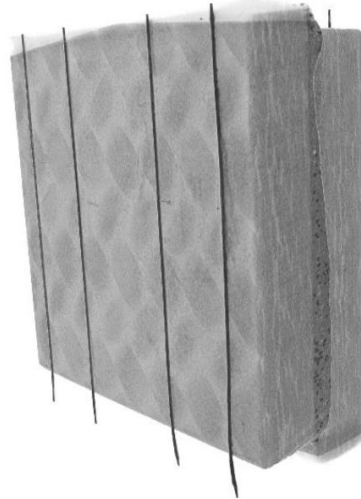


Figure 8. 3D voxel reconstruction of the specimen at 320.000 fatigue cycles.

The analysis of damage was performed observing the slices of the 3D reconstruction along suitable planes and evaluating the penetration of the contrast medium into the material. From the analysis (Fig. 9a, where the image is shown in false colours), it is worth noting damage is not characterized or dominated by a single failure mode, but both adhesive and adherends are simultaneously involved. In particular, the crack initiates in the adhesive fillet with a cohesive failure mechanism and then propagates both inside the adherends, as a delamination, and at the adhesive/adherend interface, as an adhesive failure. On the other hand, Figure 9b shows that, in the bonded plane, damage follows preferential paths related to the local configuration of the woven laminate.

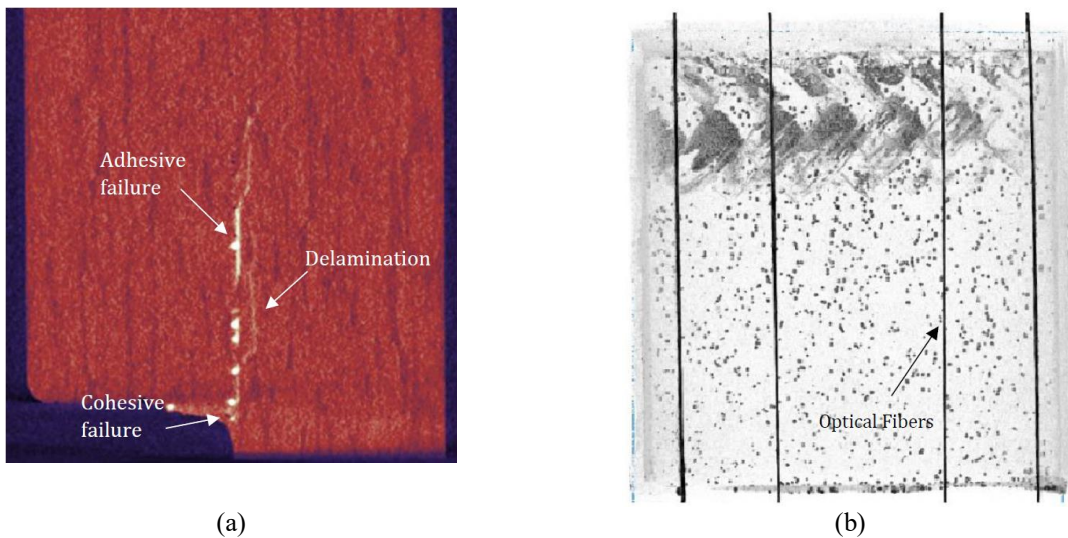


Figure 9. Damage analysis of the specimen at 320.000 fatigue cycles: a) side view; b) front view.

Thanks to the application of any suitable calibrated image processing software, it is also possible to size the dimension of the detected damage just below the paths of the optical fibre strain sensor (Fig. 10) in order to perform a comparison between the two methods.

4 Discussion

The results obtained by the different considered methods were compared to evaluate the feasibility of the SHM approach by distributed BF strain measurements. Nevertheless, the needed condition to evaluate the effectiveness of this monitoring system consists in the assessment of the validity of μ -CT data. In this regard, a way to assess the accuracy of μ -CT consists in the comparison to the lateral superficial views acquired by VT. From this point of view, the cracks observed on the lateral surfaces of the 3D reconstruction of the specimen were measured and compared to those obtained by VT (Fig. 7). Table 1 reports, as an example, the case of the specimen interrupted at 320.000 fatigue cycles.

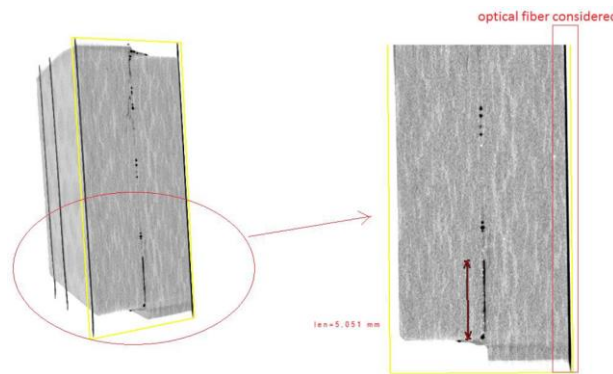


Figure 10. Example of the procedure to size damage.

	Up-right	Down-right	Up-left	Down-left
VT [mm]	5.1	5.2	6.9	4.7
μ -CT [mm]	2.4	5.4	6.7	4.7

Table 1. Comparison of damage sizes by VT and μ -CT.

As can be seen, μ -CT provides a rather accurate reconstruction of the actual shape of surface defects, except for the up-right corner of the overlapped region, where the contrast medium did not penetrate into the delamination, which, on the other hand, could be clearly seen by VT. Nevertheless, μ -CT seems to be sufficiently accurate to be a reference comparison for the results obtained by OBR. Table 2 and Figure 11 summarize and compare the sizes estimated, at 320.000 fatigue cycles, by OBR and μ -CT. Analogously, Table 3 and Figure 12 summarize and compare the sizes estimated, at 465.000 fatigue cycles, by OBR and μ -CT.

Fiber path	Front				Back			
	4	2	1	3	8	6	5	7
Peak shift (OBR) [mm]	5,2	4,6	3,3	6,5	7,8	7,2	6,5	9,8
Damage dimension (μ CT) [mm]	5,5	5,7	4,7	6,7	7,1	7,1	7,2	9,4
Average peak shift (OBR) [mm]	4,90				7,83			
Average Damage extension (μ CT) [mm]	5,63				7,70			
difference on average [mm]	-0.73				0,13			

Table 2. OBR and μ -CT at 320.000 fatigue cycles.

Fiber path	Front				Back			
	4	2	1	3	8	6	5	7
Peak shift (OBR) [mm]	10,5	10,4	11,8	7,8	8,5	7,2	6,5	11,1
Damage dimension (μ CT) [mm]	10,1	9,9	9,4	8,1	8,8	9,1	7,9	9,8
Average peak shift (OBR) [mm]	10,13				8,30			
Average Damage extension (μ CT) [mm]	9,38				8,90			
difference on average [mm]	0,75				-0,6			

Table 3. OBR and μ -CT at 465.000 fatigue cycles.

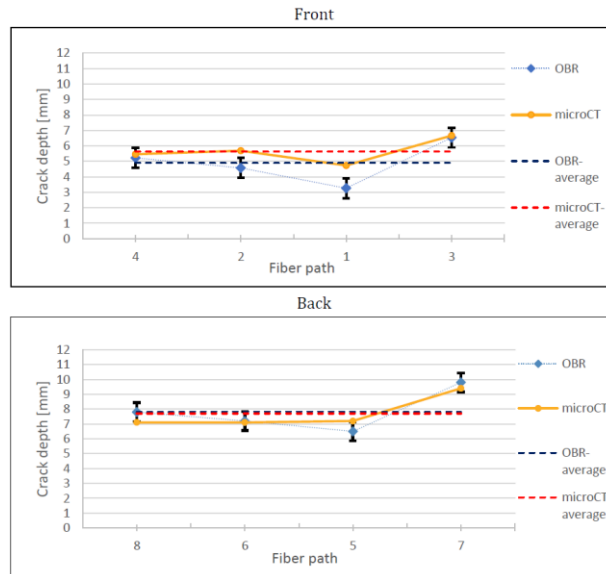


Figure 11. OBR and μ -CT at 320.000 fatigue cycles.

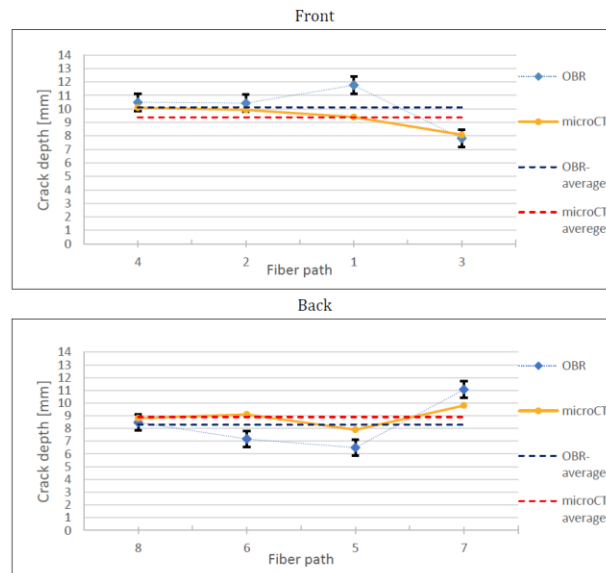


Figure 12. OBR and μ -CT at 465.000 fatigue cycles.

As can be seen, a good agreement for both trend and profile is obtained. The maximum error is about 2 mm for a damage size of about 10-12 mm, while the error on the average trend is equal to 0.5-0.6 mm, which corresponds to the spatial resolution of OBR.

In order to obtain more insight on the correlation between the position of the OBR strain peak and crack depths retrieved by μ -CT, the results listed in Tables 2 and 3 are plotted in Figure

13 together with their regression line. Such a line shows an excellent agreement with the theoretical trend (45° line), confirming the effectiveness of OBR distributed strain sensors applied to the structural health monitoring of single lap bonded joints.

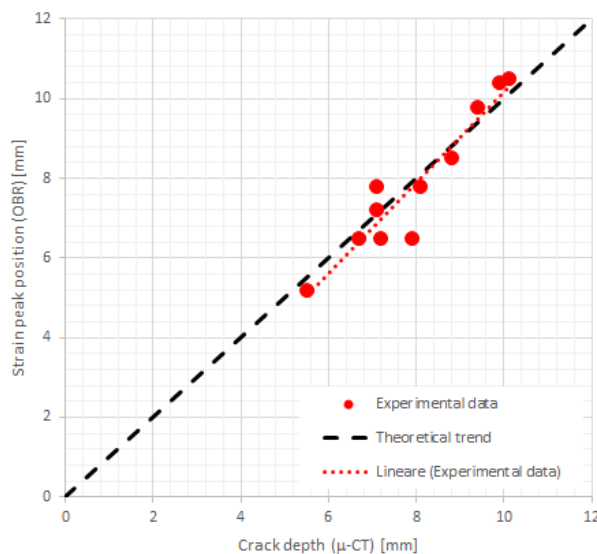


Figure 13. Position of the minimum OBR strain peak as a function of crack depth (μ -CT).

5 Concluding remarks

Based on the results presented herein, the following conclusions can be drawn:

- comparison with micro CT results confirms that BF strain monitoring by the OBR technique allows for accurate monitoring of crack growth in single lap joints, as the crack profiles identified by micro-CT are consistent with crack depth values inferred by BF measurements;
- the use of optical fiber conditioned with OBR allows for distributed strain sensing and appear to be superior to strain gauges and FBG sensors in one aspect: unlike an array of discrete strain sensors, where the positional accuracy of each sensor while gluing to the back face greatly depends on the skill of operator, this method allows for distributed sensing with good spatial resolution
- however, the present state of the art interrogators, OBR is not suitable for dynamic measurements.

Results presented herein must be considered as preliminary, as more tests are currently being conducted to strengthen these conclusions.

Acknowledgements

The authors would like to thank Dr. A. Gianneo and Mr. A. Grossi for the active help given to the experimental campaign. OBR measurements were carried out in the frame of the LAFOS Lab at Politecnico di Milano. μ -CT measurements were carried out in the frame of the AMALA Lab at Politecnico di Milano.

References

- [1] Adams, RD and Drinkwater BW, Nondestructive testing of adhesively-bonded joints NDT&E International 30, 93-98 (1997).

- [2] Zhang, Z. and Shang, J. K. A backface strain technique for detecting fatigue crack initiation in adhesive joints. *J. Adhes.* 49, 23–36 (1995).
- [3] Crocombe, A. D., Ong, C. Y., Chan, C. M., Abdel Wahab, M. M., Ashcroft, I. A., Investigating fatigue damage evolution in adhesively bonded structures using backface strain measurement. *J. Adhes.* 78, 745–778 (2002).
- [4] Bernasconi, A., Carboni, M., Comolli, L., Monitoring of fatigue crack growth in composite adhesively bonded joints using fiber Bragg gratings. *Procedia Eng.* 10, 207–212 (2011).
- [5] Bernasconi, A., Comolli, L., An investigation of the crack propagation in a carbon fiber bonded joint using backface strain measurements with FBG sensors. *Proc. SPIE* 8421, 84214Y (2012).
- [6] Canal, L. P., Sarfaraz, R., Violakis, G., Botsis, J., Michaud, V., Limberger, H. G. Monitoring strain gradients in adhesive composite joints by embedded fiber Bragg grating sensors. *Compos. Struct.*, 112, 241-247 (2014).
- [7] Sans, D., Stutz, S., Renart, J., Mayugo, J. A., Botsis, J. Crack tip identification with long FBG sensors in mixed-mode delamination. *Compos. Struct.*, 94(9), 2879-2887 (2012).
- [8] Stutz, S., Cugnoni, J., Botsis, J.. Studies of mode I delamination in monotonic and fatigue loading using FBG wavelength multiplexing and numerical analysis *Compos. Sci. Technol.*, 71(4), 443-449 (2011).
- [9] da Silva, L. F. M., Moreira, P. M. G. P., Loureiro, A. L. D. Determination of the strain distribution in adhesive joints using Fiber Bragg Grating (FBG) *J. Adhes. Sci. and Tech.*, 28 (14-15), 1480-1499 (2014).
- [10] Sanderson, A. R., Ogin, S. L., Crocombe, A. D., Gower, M. R. L., Lee, R. Use of a surface-mounted chirped fibre Bragg grating sensor to monitor delamination growth in a double-cantilever beam test. *J. Compos. Sci. Technol.*, 72(10), 1121-1126 (2012).
- [11] Capell, T.F, Palaniappan, J., Ogin, S. L., Crocombe, A.D., Reed, G.T., Thorne, A.M., Mohanty, L., Tjin, S.C.. The use of an embedded chirped fibre Bragg grating sensor to monitor disbond initiation and growth in adhesively bonded composite/metal single lap joints. *J Optics A – Pure and Applied Optics*, 9-6, 40-44 (2007).
- [12] Palaniappan, J., Wang, H., Ogin, S. L., Thorne, A. M., Reed, G.T. Crocombe, A.D., Mohanty, L., Rech, Y., Tjin, S.C.. Changes in the reflected spectra of embedded chirped fibre Bragg gratings used to monitor disbonding in bonded composite joints. *Comp Sci and Tech*, 67, 2487-2853, (2007).
- [13] Güemes, A., Fernandez-Lopez, A., Soller, B. Optical fiber distributed sensing-physical principles and applications. *Struct. Health Monitor.* Vol 9(3): 233–45 (2010).
- [14] Frövel, M., Del Olmo, E., Fernández, A., Quero, F., Carrión, G., Pintado, J.M., Güemes, A. *Damage detection by load path changes in reinforced composite panels using local FBGS and distributed sensing.* Proceeding of 6th European Workshop on Structural Health Monitoring (2012)
- [15] Grave, J.H.L., Håheim, M.L., Echtermeyer, A.T. *Evaluation of the strain field in a composite - metal adhesive joint with an optical backscatter reflectometer.* Proceeding of the 15th European Conference on Composite Material, ECCM, 2012
- [16] Bernasconi, A., Kharshiduzzaman, M., Comolli, L., Strain Profile Measurement for Structural Health Monitoring of Woven Carbon-fiber Reinforced Polymer Composite Bonded joints by Fiber Optic Sensing Using an Optical Backscatter Reflectometer. *J. Adhes.* 92, 440-459 (2016)
- [17] A Bernasconi, M Carboni, L Comolli, R Galeazzi, A Gianneo, M Kharshiduzzaman, Fatigue crack growth monitoring in composite bonded lap joints by a distributed fibre optic sensing system and comparison with ultrasonic testing. *J. Adhes.* 92, 739-757 (2016)