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Monitoring Crack Tip Position in Adhesively Bonded Joints Under Mixed I+II Mode Loading

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Abstract. The use of adhesive joints has gained favour in recent years, due to their capacity for weight reduction, improved stress distribution, and enhanced fatigue resistance. However, the widespread use of adhesive joints in structural applications is hindered, because reliable and mature inspection and defect detection techniques are not yet available. Adhesive joints in structural applications are subject to fatigue loading, during which debonds can initiate and propagate, ultimately leading to potential failure. In the majority of cases, joints operate under mixed-mode loading conditions. In this work, a steel Cracked Lap Shear specimen was tested to investigate the crack growth behaviour of adhesive joints under mixed I+II mode loading. To address the challenge of monitoring these joints, a range of experimental techniques was employed. These techniques included Visual testing, Digital Image Correlation, and Optical Backscatter Reflectometry. The different methods were evaluated and compared to determine their effectiveness in locating the crack tip within joints during fatigue propagation.

Keywords: Adhesively bonded joints, Cracked Lap Shear Specimen, crack tip localization, Mixed Mode Fatigue

Introduction

High strength-to-weight ratio, design flexibility, multi-material joints, and more uniform stress distributions are the reasons why adhesively bonded joints are becoming a widely used joining technique in several industrial applications [1,2]. However, adhesively bonded joints may suffer from damaging due to working loads and environmental conditions, which can cause cracks to initiate and propagate. For this reason, it is important to study the fatigue behaviour of adhesively bonded joints, and to develop methods to check their in-service structural integrity.

Many studies have investigated mode I crack propagation [3–5], as adhesives typically have a lower fracture resistance in mode I than in mode II. For the same reason, however, structures are designed to favour mode II loading and reduce mode I loading [6]. In practice, most joints experience a mixed (I + II) mode loading condition [7], but only few studies so far have investigated mixed mode loading [8–11].

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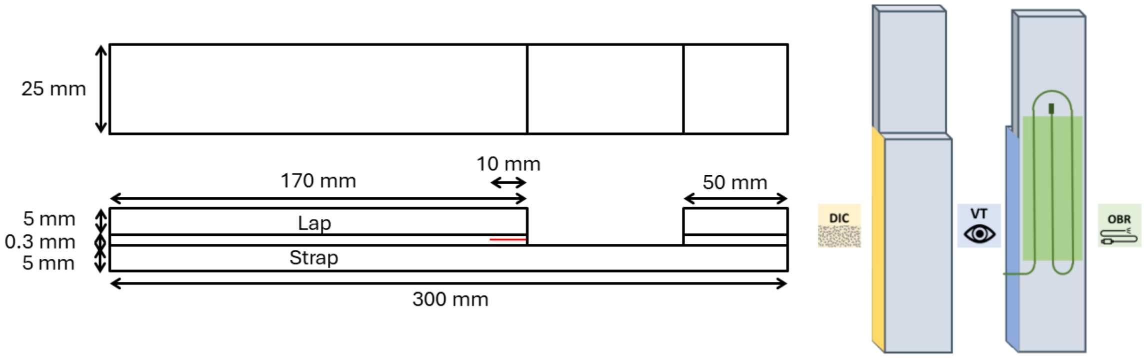
In this work, a fatigue test was conducted on an adhesively bonded Crack Lap Shear (CLS) steel specimen. Throughout the test, crack propagation was monitored using Visual Testing (VT), Digital Image Correlation (DIC), and backface strain monitoring using Optical Backscatter Reflectometry (OBR).

Studying the fatigue crack propagation of adhesively bonded joints will help in ensuring safety, furthermore, evaluating different crack tip monitoring techniques will help in the development of suitable sensing systems for application in industry.

1. Materials and Methods

1.1 Specimen Preparation

A CLS specimen was manufactured from high strength AISI A514 steel adherends bonded with 3M Scotch-Weld 9323 epoxy adhesive. The dimensions of the specimens are given in Figure 1a.



(a) (b)

Figure 1: (a) Specimen Dimensions. (b) Monitoring scheme.

The substrates were sandblasted and thoroughly cleaned with acetone before bonding. Glass microspheres (300 μm diameter) were added to the adhesive with a concentration of 1% by weight of total adhesive. A razor blade was placed in the adhesive layer to create an initial notch. The specimens were cured in an oven at 65°C for two hours.

The two lateral sides of the specimen were sanded to remove the excess adhesive. The specimen was monitored according to the scheme shown in Figure 1b. One side was used to perform VT. The surface was coated with a white brittle paint, and a ruler attached close to the bondline to measure the crack length. The other side was prepared for DIC analysis by painting it white and then creating a speckle pattern using a black spray paint. DIC pictures were taken using a 26.2 Canon EOS-RP camera equipped with a Canon RF 85 mm F2 macro IS lens which allowed a resolution of 46.4 pixel/mm. Image processing was done using GOM Correlate 2020. A subset size of 19 pixel (0.41 mm) and a point distance of 16 pixel were chosen (see Figure 2).

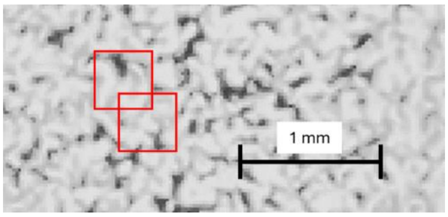
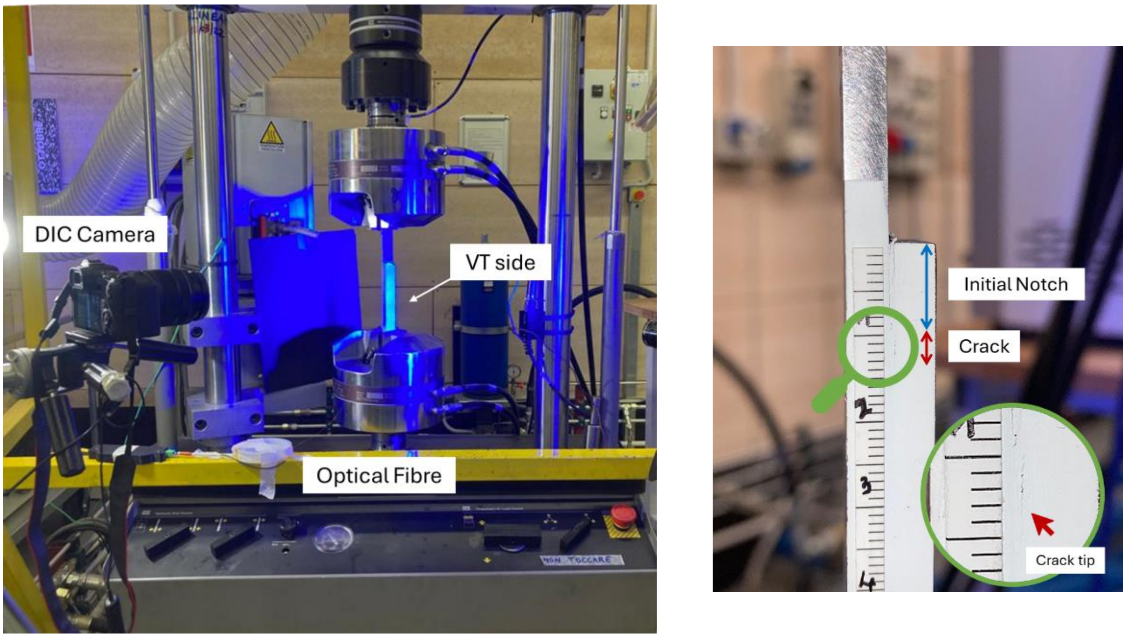


Figure 2: DIC Speckle pattern with the subset size highlighted.

For backface strain monitoring using OBR, a high-definition low bending loss optical fibre was bonded on the strap of the specimen using 3M X100 adhesive. Three paths were obtained by bending the fibre (see Figure 1b). The fibre was connected to an optical backscattered reflectometry (OBR) interrogator ("ODiSI-B" by Luna Innovation Inc.) which allows a spatial resolution of 0.625 mm and an acquisition frequency of 23.7 Hz.



(a) (b)

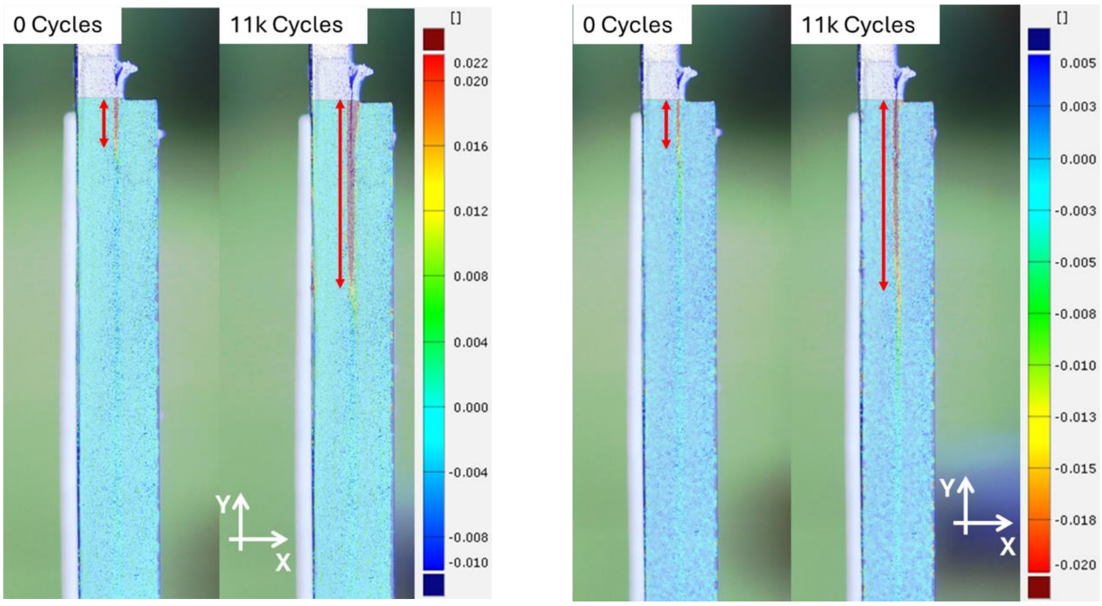
Figure 3: (a) Fatigue test setup. (b) Visual Testing Example.

Fatigue tests were conducted on a MTS Landmark 810 hydraulic tensile test machine equipped with a 100 kN load cell (see Figure 3a). The specimen was tested at a load ratio of 0.1 and a frequency of 5 Hz and the applied peak load was increased from 30 to 50 kN during the test so that different values of strain energy release rate could be obtained. Fatigue cycling was interrupted at regular intervals, then a ramp was performed up to 30 kN, which was held for some time to allow for DIC and OBR acquisitions. During the hold times the crack length was also measured by VT (see Figure 3b).

2. Results and discussion

Digital Image Correlation was used to observe the deformation of the adhesive layer. Since rotations are quite small, it is possible to separate the mode I and mode II components by considering deformations and displacements in the x- and y- directions, respectively. This can provide useful information on how the joint is behaving under the applied load.

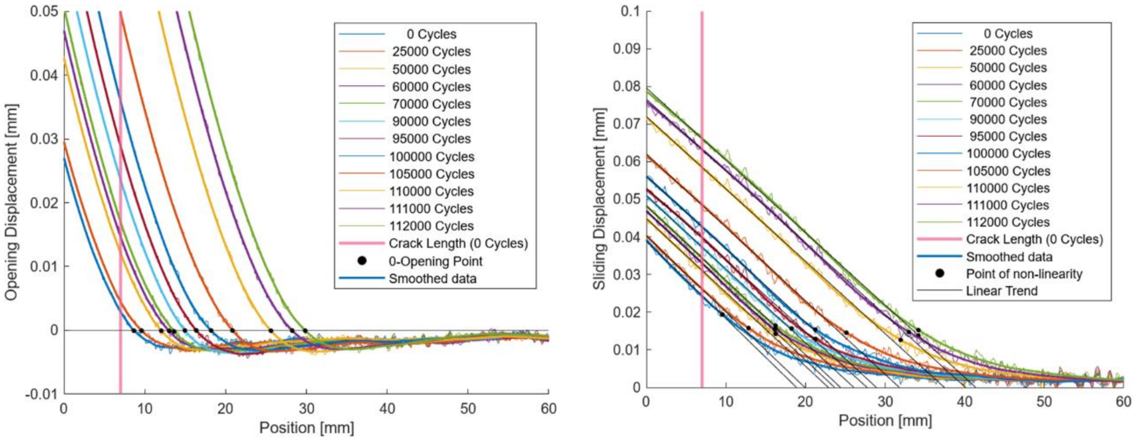
Figure 4 shows the peel and shear strain fields at two stages of the fatigue test. The crack length measured by VT is highlighted. The opening strain component is quite high at the crack tip, but quickly reduces (Figure 4a), on the other hand, it is possible to observe that a significant length of the adhesive is under shear strain (Figure 4b).



(a) (b)

Figure 4: (a) Peel strain (mode I) and (b) Shear strain (mode II) in the specimen at 0 and 11k cycles. The crack length measured by VT is indicated by red arrows.

Opening and the sliding displacements in the bondline were obtained by measuring the relative displacements between the two substrates, according to the method described in [8]. Their trends are shown in Figure 5a and Figure 5b. The opening displacement has a non-linear trend, it is higher at the crack tip, but quickly becomes negative. The sliding displacement displays a linear trend in the cracked portion of the bondline, then, it decreases to a constant, positive, value. To locate the crack tip position, the position where the opening displacement was equal to 0, and the point in which the sliding displacement ceased to have a linear trend were obtained for each acquisition.



(a) (b)

Figure 5: DIC bondline displacements: (a) Opening displacement. (b) Sliding displacement.

Figure 6 shows the backface strain measured at the beginning of the fatigue test. The beginning and end points of the three paths were localized using a hot resistance and the touch to locate function so that each strain value could be associated to a specific position on the specimen, as shown in Figure 7a. The baseline measurement shows that the strain profile of all three paths presents a local minimum at the crack tip location. As the specimen was fatigued, and the crack propagated, the strain profile evolved, and the local minimum gradually shifted. The position of the minimum was obtained for each acquisition.

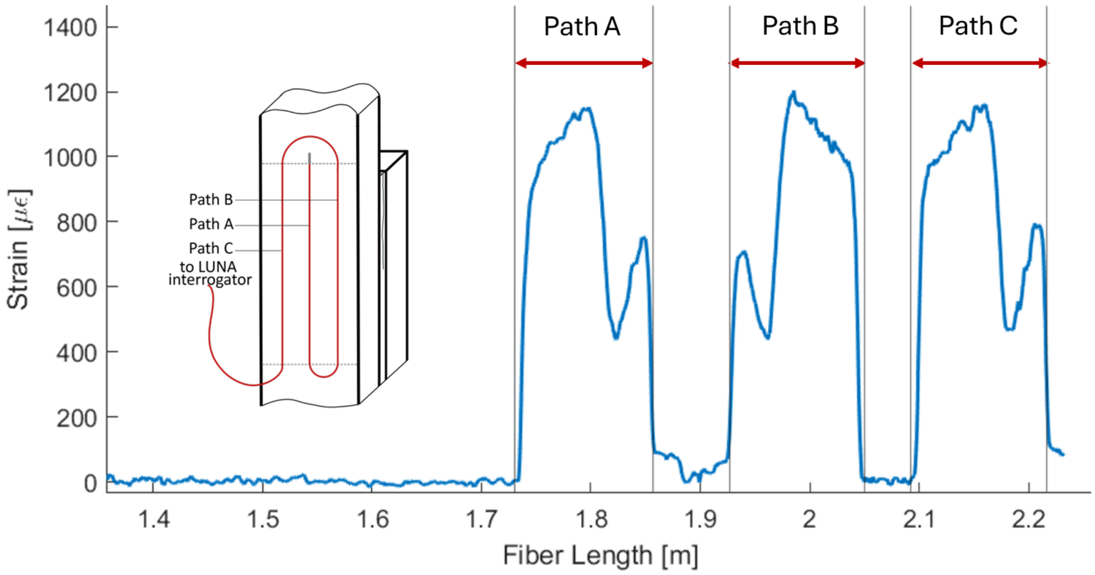
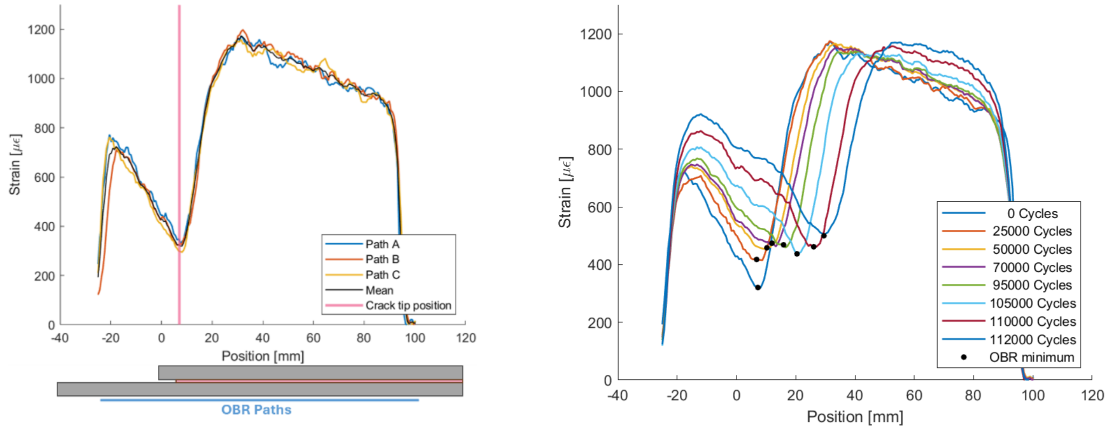


Figure 6: Baseline OBR acquisition.



(a) (b)

Figure 7: (a) Backface strain profile at the beginning of the fatigue test. (b) Evolution of the backface strain profile during fatigue testing.

Figure 8 compares the crack length estimations obtained by this method with VT measurements. Due to noise in the strain measurement, there is some variability in the trends of the three individual paths. Averaging over the three paths shows a clearer trend. On most acquisitions the crack estimated by OBR is longer than the one measured by VT.

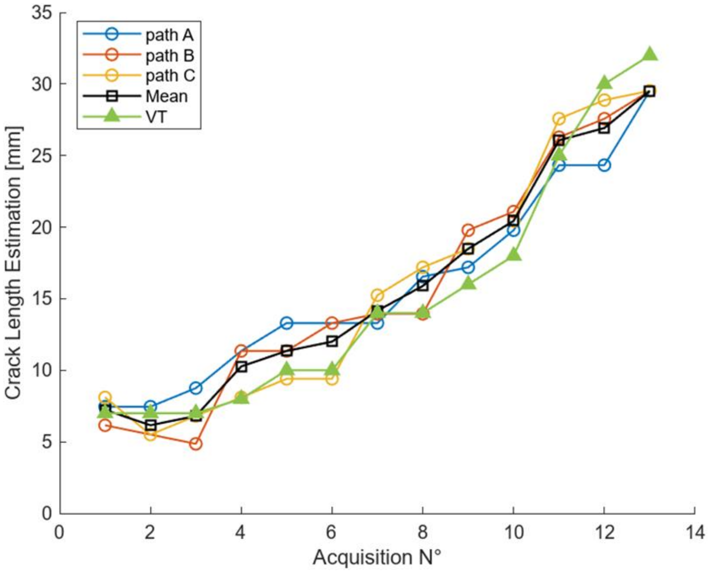


Figure 8: Crack length estimation by OBR and comparison with VT measurements.

In Figure 9 a comparison of all techniques used is made. Both DIC and OBR measurements consistently yield longer crack length measurements than VT. The two methods measure deformations, rather than stresses, so it is possible that these differences are due to the presence of a fracture process zone. Additional numerical and experimental analysis is being undertaken to further understand this phenomenon.

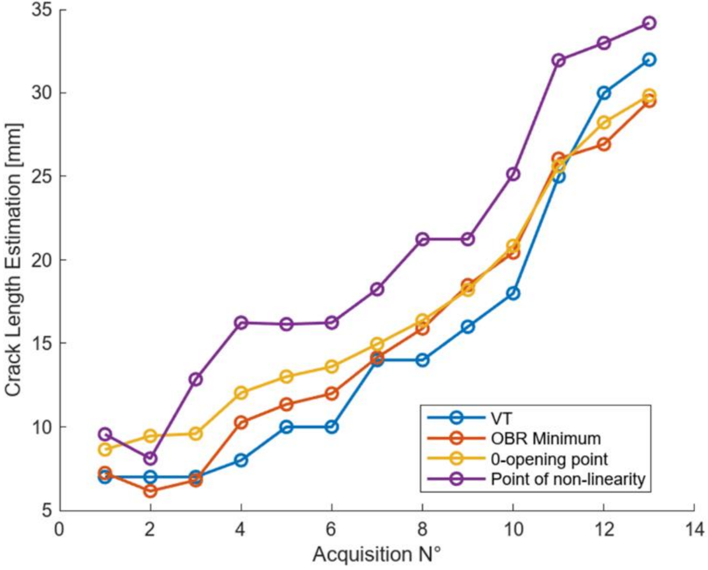


Figure 9: Comparison of VT, OBR, and DIC crack length estimations.

3. Conclusions

Investigating fatigue crack propagation in adhesively bonded joints requires that reliable crack length measuring techniques are developed.

In this study, an adhesively bonded Cracked Lap Shear steel specimen was tested to investigate crack propagation under mixed mode loading conditions. The crack tip was monitored using Visual Testing, Digital Image Correlation, and backface strain monitoring by Optical Backscatter Reflectometry. Their effectiveness in identifying the crack tip was compared and evaluated. The use of multiple monitoring techniques is recommended to obtain reliable crack length measurements, as VT may not always provide accurate results.

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