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Monitoring crack tip position in Cracked Lap Shear specimens subjected to fatigue loading

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Abstract

In recent years, interest in adhesively bonded joints has significantly grown, as it offers numerous advantages with respect to other joining techniques. Bonded joints are being increasingly adopted in structures subjected to fatigue loading, which might initiate and propagate crack-like debonding defects. The ability to detect and locate these defects is crucial for increasing overall safety. This study aims to investigate the capability of two commonly used Non-Destructive techniques, namely Digital Image Correlation and Visual Testing, to correctly locate the crack tip of a debonding damage. For this purpose, a specific Cracked Lap Shear specimen, which features mixed mode I-II loading conditions, was designed, manufactured, and tested under fatigue loading. Two different adhesives were used. The results showed that Digital Image Correlation was able to easily identify the crack tip, while visual inspection proved to have some difficulties due to the prevalence of mode II, which makes crack identification more troublesome.

KEYWORDS: Adhesively bonded joint; fatigue; damage monitoring

1. Introduction

Adhesive joining provides many advantages over conventional mechanical methods, such as lower structural weight, easier manufacturing, and lower stress concentrations [1]. Despite the many advantages, its use in structural joints is limited by the current lack of suitable Non-Destructive Testing (NDT) techniques able to detect and evaluate defects in the joints, especially those due to fatigue crack propagation [2]. Fracture in an adhesively bonded joint is usually a mixed-mode problem, as shear and peel stresses are generally present in an adhesive layer [3].

To test mixed mode crack propagation, the Cracked Lap Shear (CLS) specimen is often used, which has the characteristic that its total strain energy release rate (SERR) is constant for all crack lengths [4].

Many studies used Digital Image Correlation (DIC) to monitor crack propagation in adhesively bonded joints [5, 6], but only few studied crack propagation under mixed mode loading [7].

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Given the importance of the topic, this work aims to evaluate the use of DIC and Visual Testing (VT) for monitoring of crack tip position of adhesively bonded joints subjected to mixed-mode fatigue loading.

2. Materials and Methods

2.1 Design and Manufacturing of Specimens

CLS specimens were manufactured out of 5mm thick high strength AISI A514 stainless steel plates and bonded using two different types of adhesives, 3M DP490 [8] and 3M 9323 [9]. The dimensions of the specimens are given in Figure 1, while the mechanical properties of the adherends and of the adhesives are given in Table 1.

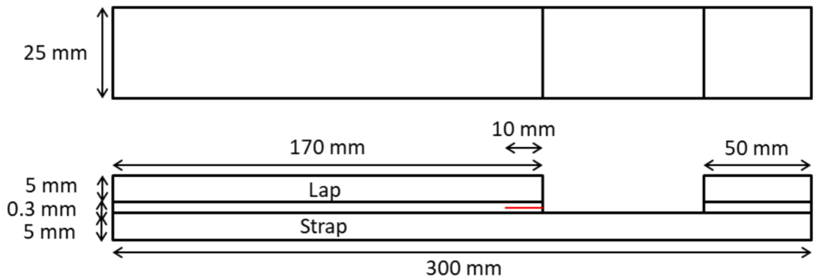


Figure 1: Nominal dimensions of the CLS specimens

Table 1: Mechanical properties of DP 490 and 9323 adhesives

	DP 490	**9323**
E (MPa)	1730	2600
ν	0.43	0.35
G_{IC} (N/mm)	2.7	2.8
G_{IIC} (N/mm)	10.8	10.8

The steel pieces were sanded and cleaned to obtain a suitable surface for bonding. Four specimens (#1 to #4) were bonded using the 3M DP490, one (#5) with the 3M 9323. 1% by weight of glass microspheres with a diameter of 0.3 mm were added to the 9323 adhesive to control bond thickness. Strips of Teflon tape were applied to both the strap and the lap to obtain a 10 mm precrack. The specimens were then clamped and cured in an oven at 65° for at least 2 h.

A white brittle coating paint was applied to one side of the specimen to perform VT, and a white coating paint with a black speckle on the other side, for monitoring by DIC.

2.2 Fatigue tests

Fatigue tests were carried out on an MTS 370 servo-hydraulic testing machine equipped with a 100kN load cell. The maximum load was set at 20kN, the load ratio was 0.1, and the frequency 5Hz, to avoid overheating of the adhesive. The tests were interrupted at regular intervals and the specimen brought to max load to acquire DIC pictures and perform VT inspection. GOM Correlate 2020 was used to post-process DIC pictures.

3. Results and discussion

3.1 Visual testing

Figure 2.a shows crack propagation at three points during a fatigue test. The use of white brittle coating relies on the presence of stresses perpendicular to the fracture line (i.e., on the mode I component), which open the crack and make it visible, but identifying the crack tip in mode II is more difficult. In this setup, while it is easy to see that propagation is taking place, the predominance of mode II makes pinpointing the exact crack tip position rather difficult (see Figure 2.b).

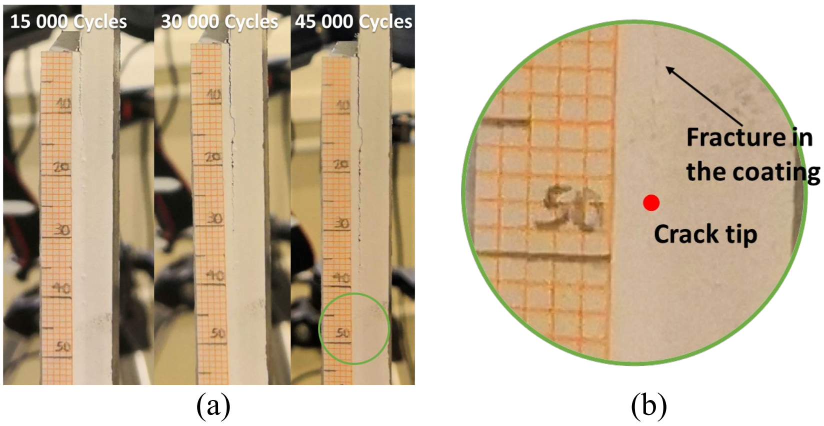


Figure 2: Visual inspection: (a) examples pictures taken at different points during a fatigue test (specimen #1) to measure crack propagation; (b) detail of the picture taken at 45 000 cycles

The crack growth trends obtained with visual inspection are shown in Figure 3. Being the SERR constant, a constant crack propagation speed is expected throughout the test, as well as between different tests on the same adhesive.

However, this is not the case for the performed tests, as the specimens bonded with 3M DP490 shows different crack propagation speeds. Furthermore, specimens #2 and #3 show an irregular trend. This could be also due to the difficulties in identifying the crack tip exactly. Under the same applied load, crack propagation started immediately for all specimens bonded with the 3M DP490 adhesive, while the one bonded with 3M 9323 showed no propagation for the first 24 000 cycles (Figure 3.b), after which crack propagation followed the expected linear trend.

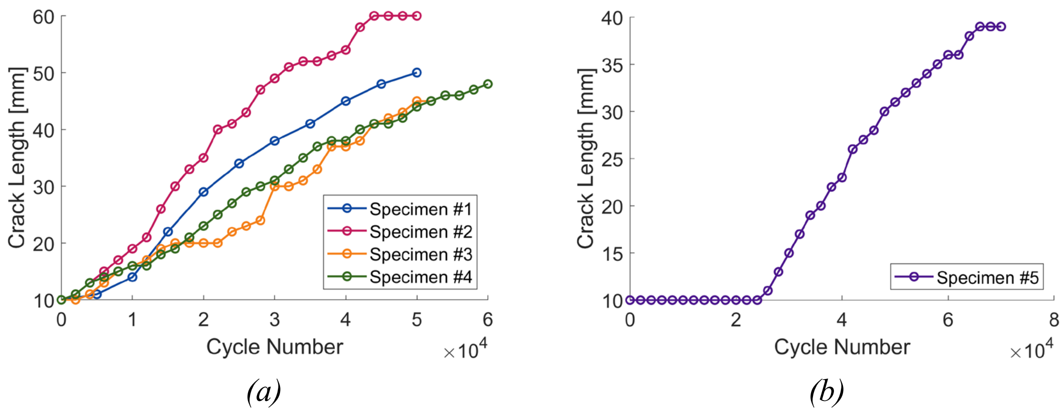


Figure 3: Crack propagation as measured by Visual Testing. (a) specimens #1 to #4 bonded using 3M DP490 (b) specimen #5 bonded using 3M 9323

3.2 Crack tip monitoring using digital image correlation

For what concerns DIC, the technique applied to identify the crack tip in this analysis is the same as that developed by Zhu et al.[5] for crack propagation under pure mode I. The displacement field in the y-direction (i.e., the mode I contribution) (see Figure 4), is uniform in the cracked zone, but shows a discontinuity where the crack is present. Using GOM Correlate, a series of virtual extensometers straddling the bondline was created. The virtual extensometers are 2 mm long and 0.5 mm apart.

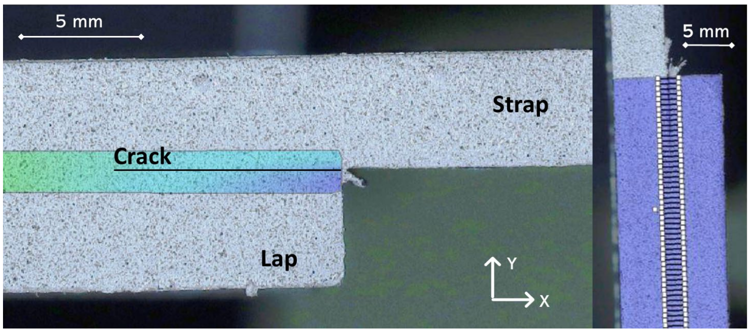


Figure 4: Detail of the y-displacement around the bondline (left) and virtual extensometers used for the analysis (right)

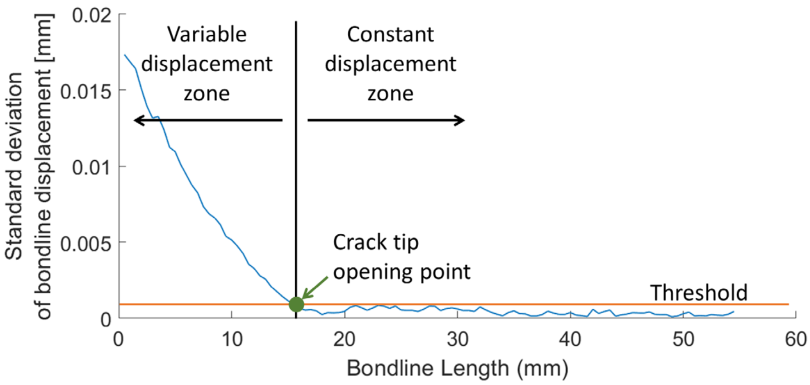


Figure 5: Exemplificative plot of the standard deviation of bondline displacement trend over the bondline length (specimen #1, 10,000 cycles)

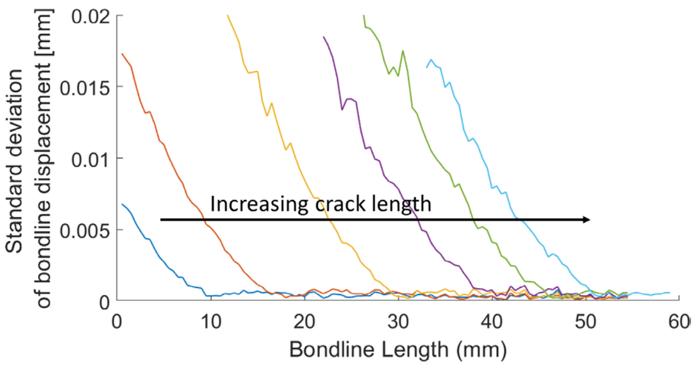
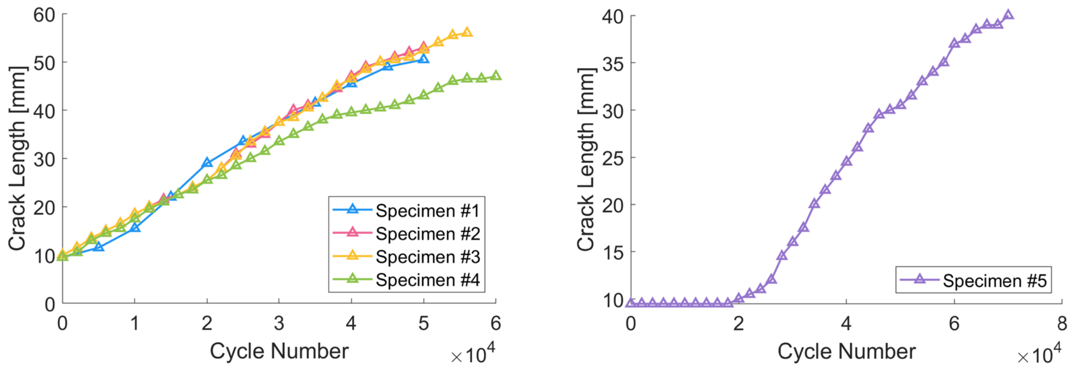


Figure 6: Standard deviation of bondline displacement trends for increasing crack lengths

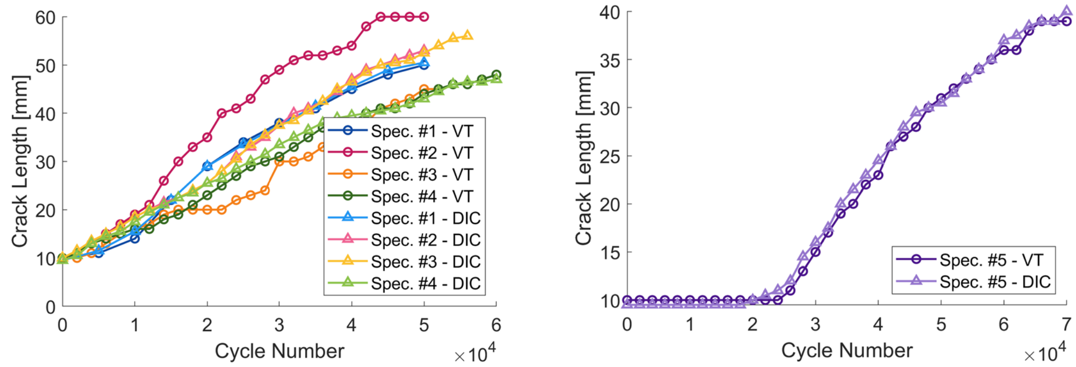
Displacement values were extracted for 14 points along each extensometer, and their standard deviation computed.

By plotting the standard deviation over the bondline length (see Figure 5) it is possible to observe a ligament, with low and almost constant variability, and an area where the standard deviation increases dramatically. As crack propagation progresses, the standard deviation trend mantains a similar shape, but shifts along the same direction of crack propagation (Figure 6). To identify the crack tip opening point the maximum peak recorded in the constant displacement zone is set as a threshold.
Figure 7 shows the crack growth trends obtained by DIC, while Figure 8 compares them with VT. It can be seen that crack growth trends obtained by DIC are more linear and show very similar crack growth speeds within the four specimens bonded with the same adhesive (see Figure 7.a). In Figure 8 it is possible to see that VT and DIC trends diverge significantly for specimens #2 and #3, for which VT showed irregular trends, while they are in close agreement for specimens #1, #4, and #5. Interestingly, for specimen #5, DIC was able to detect the onset of crack propagation 6000 cycles earlier than VT (Figure 8.b). Linear regression was performed to gauge the linearity of the crack propagation trends. The R^2 index was higher than 0.96 in all tests, with DIC showing on average higher values, indicating a more linear trend.
The predominance of mode II loading makes identifying precisely the crack tip location challenging, but, based on these on these results, DIC appears to have performed better than VT.



(a) (b)

Figure 7: Crack propagation as measured by DIC for (a) specimens #1 to #4 bonded using 3M DP490 and (b) specimen #5 bonded using 3M 9323



(a) (b)

Figure 8: Comparison of crack propagation trends measured by VT and DIC for (a) specimens #1 to #4 bonded using 3M DP490 and (b) specimen #5 bonded using 3M 9323

4. Conclusions

The objective of this work was to analyse the effectiveness of VT and DIC in identifying the crack tip in an adhesive joint subjected to mixed mode fatigue. A CLS specimen with steel adherends was chosen for the research.
Two different adhesives were used. For 3M DP490 crack propagation started immediately upon fatigue loading, while for 3M 9323 a crack initiation phase was recorded.
The predominance of mode II loading makes crack tip identification difficult, still, DIC was able to monitor crack propagation, and showed a better performance compared to VT. As already shown for mode I [5], there is high variability in the opening displacement where a crack is present, and this can be used to reliably identify the crack tip position. DIC was also able to identify the onset of crack propagation earlier than VT.

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