Acoustic Emission during Fatigue Crack Growth in Aluminium Plates

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Abstract. Acoustic emission (AE) is potentially an ideal technique for health monitoring of large structures due to the small number of sensors required and its high sensitivity. There has been much research conducted to characterize and provide qualitative understanding of the AE process in small specimens. Unfortunately, it is difficult to extend these results to real structures as the experimental data is dominated by geometric effects due to the small size of the specimens.
The aim of this work is to provide a characterization of elastic waves emanating from fatigue cracks in plate-like structures. Fatigue crack growth was initiated in large 6082 T6 aluminium alloy plate specimens subjected to cyclic loading in the laboratory. A large specimen was used to eliminate signal reflections from the specimen edges and to enable signals from different wave modes to be separated in time. The signals were recorded using both resonant and non-resonant transducers attached to the surface of the specimens. Large numbers of AE signals were detected due to active fatigue crack propagation during the experiment. Analysis of experimental results from multiple crack growth events was used to characterize the modal and angular distributions of the radiated elastic waves. Experimental results are compared with finite element predictions to examine the mechanism of AE generation at the crack tip.

Introduction

Acoustic emission testing is a technique for evaluating and monitoring progressive defects in structural component [1]. The release of stress waves from fatigue cracks in the structures under loading are detected using piezoelectric transducers mounted on the surface [2]. The majority of publications show qualitative results from at test pieces varying in size from small fatigue test specimens [3] to complete aerospace structures [4]. A small number of publications show quantitative results from fatigue cracks in bulk materials [5, 6] and there is limited work showing quantitative results from plate-like structures [7, 8]. Elastic waves generated from fatigue cracks in a large isotropic plate-like structure are analysed in this paper to produce quantitative analysis. The use of a large plate permits the sensors and the crack tip to be positioned far apart thereby enabling the lower frequency wave modes to be separated in time. In additional, it also removes the effects of multiple reflections and mode conversion. The on-going experimental work shows that the elastic waves emanated from the fatigue crack can be characterized using guided wave analysis.

Finite element (FE) simulations have been employed to provide better understanding into wave propagation problems [9]. In this paper, 2D and 3D FE simulations have been used to model the AE waves from fatigue crack growth. It can also provide a better understanding of the modal and angular distribution of the radiated elastic waves generated from the fatigue crack tip in plates.

Experiment and results

1.1 Experimental setup

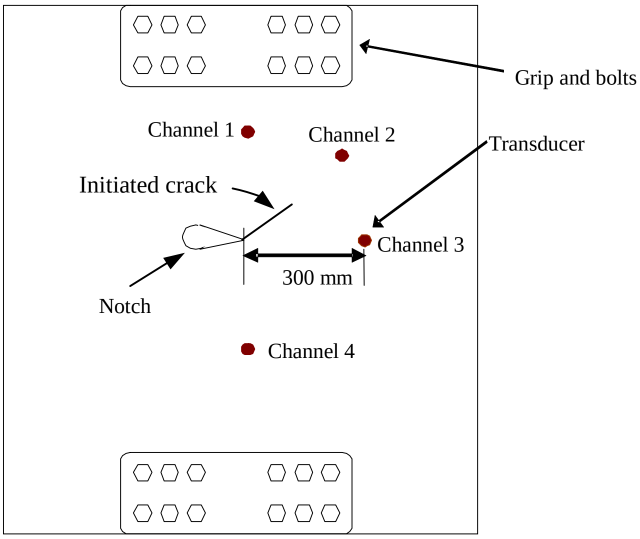
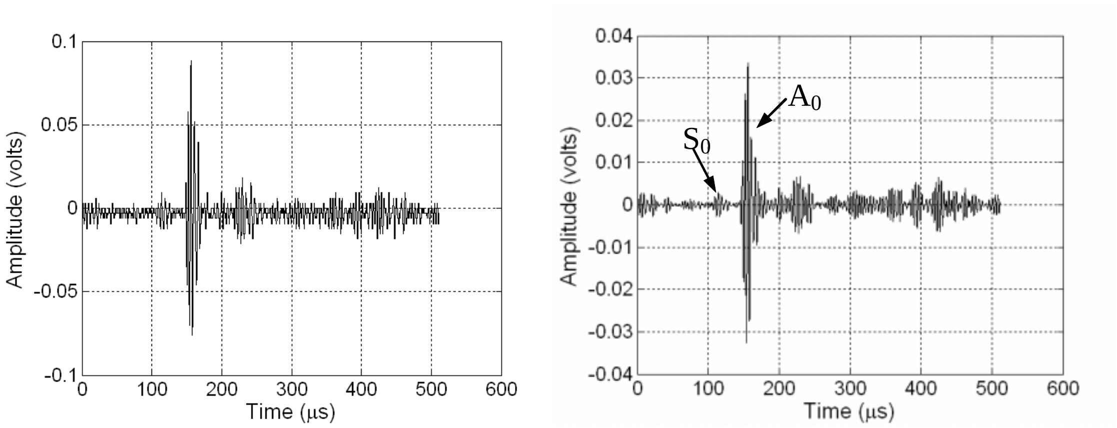


Figure 1. Fatigue test setup indicating location of sensors.

A fatigue test machine (DARTEC 500) was used to fatigue a large (1200 x 1000 mm x 3 mm thick) 6082 T6 aluminium alloy plate. Figure 1 shows the setup for the fatigue testing and the location of the transducers. A notch with a sharp tip at the end was created in the centre of the plate to act as a crack initiator. The grips to attach the specimen to the fatigue test machine were carefully designed to ensure that the highest stress was at the tip of the crack initiator at the centre of the plate. Four transducers were placed 300 mm away from the tip of the crack. A commercial AE system (Physical Acoustics Corporation, PCI2) was used to detect and record the AE signals. Two Physical Acoustics Corporation, type WD transducers (bandwidth 100 kHz – 600 kHz) at channels 2 and 4 and narrowband transducers (centre frequency 250 kHz) at channels 1 and 3 were used.

1.2 Wave modes

The fatigue test machine ramped from 0 to 150 kN and then a cyclic loading from 100 kN to 200 kN at a frequency of 3 Hz was applied. Following the initiation of a fatigue crack, the frequency was reduced to 1 Hz to maintain slow crack growth. After several hours of loading, AE signals began to be registered by all 4 channels. Figure 2(a) shows a typical recorded waveform from channel 1. The signal was filtered in *Matlab* using a Gaussian window with 250 kHz centre frequency and bandwidth of 350 kHz. The filtered waveform shows distinct S_0 and A_0 modes as shown in Figure 2(b).



(a) (b)

Figure 2. AE signal recorded from channel 1 (a) waveform showing distinct S_0 and A_0 (b) filtered signal.

The experimental work in this paper has clearly shown that acoustic waves from fatigue crack growth propagate as guided waves. The amplitude of the S_0 and A_0 signals in each AE waveform from channel 1 were collected and the results are plotted in figure 3. It was observed that the ratio between the amplitude of the A_0 and S_0 Lamb wave modes remains relatively constant over the duration of the test.

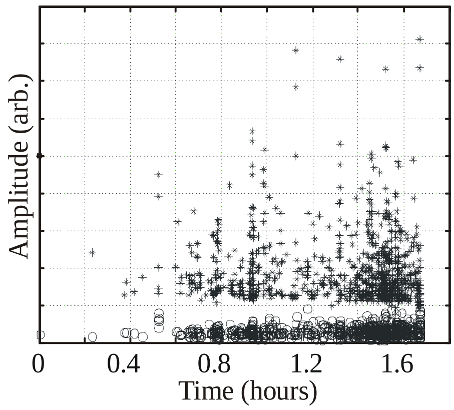


Figure 3. Amplitude of the S_0 (open circles) and A_0 (asterisks) modes over the duration of the fatigue test.

In order to determine the angular distribution of radiated waves from fatigue crack, more data points are needed. Due to the difficulty of obtaining experimental data, finite element numerical simulations have been used to provide more extensive parametric data which is then backed up with experimental data. It is hoped that in the future experimental work, more transducers are to be placed around crack tip to monitor the AE signals in a radial pattern.

Finite element modelling of acoustic emission from crack growth

2D FE simulations have been performed to provide further information on the behaviour of the wave modes emitted from various crack depths. 3D FE simulations have been used to investigate the angular distribution of radiated waves from crack growth. The FE modelling is based on linear elasticity assumptions and is undertaken using *ABAQUS* software.

2.1 2D FE modelling of crack growth

FE was used to simulate the acoustic wave generated from fatigue crack growth in the plate. The basic procedure is shown in figure 4. First the model is subjected to a static load and then the nodes at the crack growth location are released causing guided wave excitation. Due to symmetry about the crack face, only half of the plate needs to be modelled.

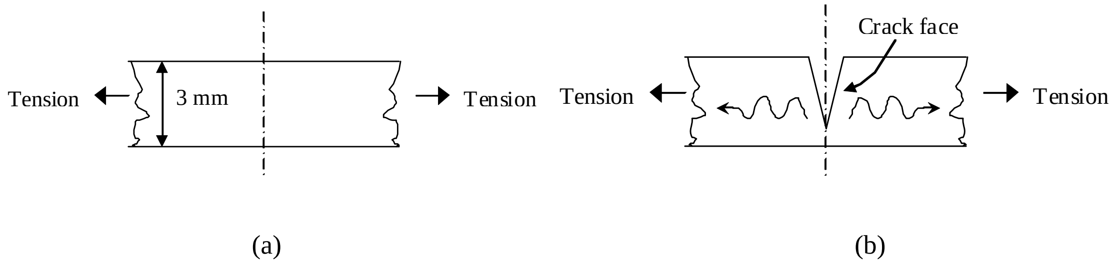


Figure 4. Crack through the thickness of the plate (a) before and (b) after crack growth.

The model used four noded, plane strain elements with eight elements through the thickness of the plate. With eight elements, the element size was calculated to be 0.375mm and a time step of 10 ns was used. The mesh just after the release of four nodes together to simulate a crack growth of 1.5 mm depth is as shown in figure 5.

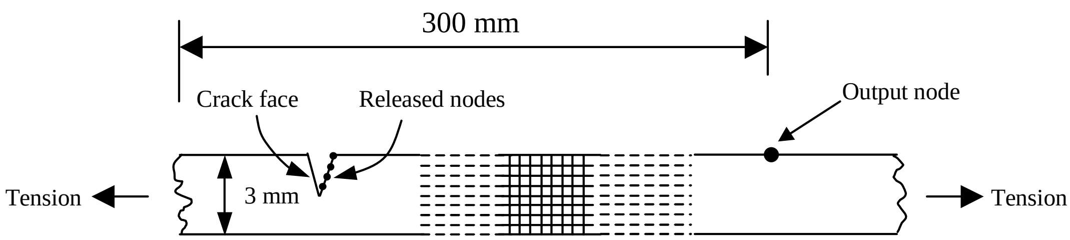


Figure 5. Cracking through the thickness of the plate.

This sudden release of nodes resulted in high frequency components in the wave signals. It is clear that the propagation of these components cannot be modelled accurately as the number of elements per wavelength in the model is not high enough. However, these high frequency components can be easily filtered out by post-processing of the received time-domain signals. Figure 6(a) shows the recorded waveform from the crack tip. The waveform was post-processed by using the same Gaussian window as used to filter experimental data. The filtered result in Figure 6(b) shows distinct S_0 and A_0 modes.

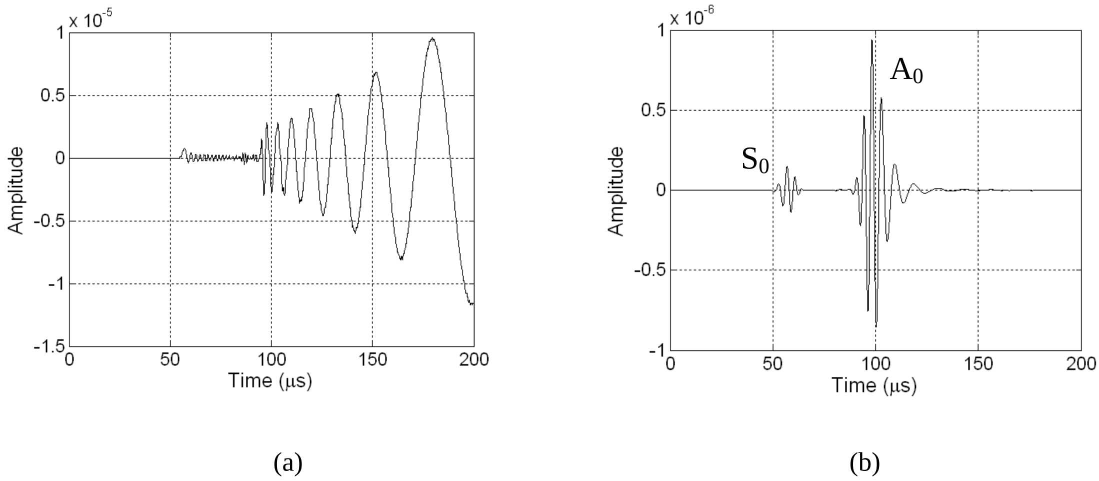


Figure 6. Typical results from FE model: (a) recorded signal from output node and (b) the signal after filtering its frequency spectrum showing separation of the S_0 and A_0 modes.

Different crack depths were investigated and the different wave modes were characterized. The amplitude of the A_0 and S_0 modes from different fatigue crack depths through the plate thickness is plotted in figure 7. It is interesting to note that as the depth of the crack is increased there is only a gradual increase in the amplitude of the S_0 mode and the A_0 mode has the highest amplitude for the majority of different fatigue crack depths. It was noted that only fatigue crack depth of more than about 86% generated higher amplitude of S_0 than A_0.

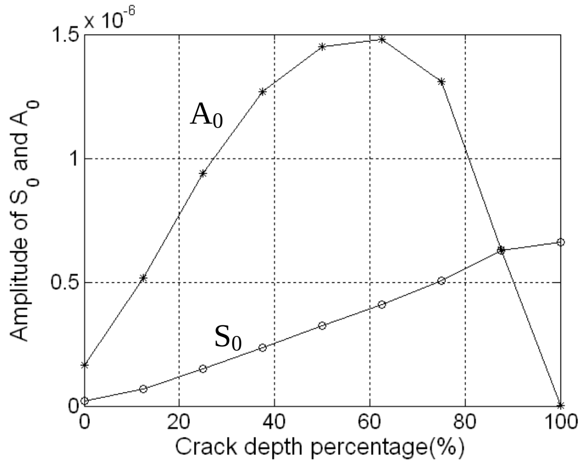


Figure 7. Collection of the amplitude of the S_0 and A_0 modes from different fatigue crack depths.

2.2 3D model to simulate radial pattern from a fatigue crack with pre-crack

FE was used to simulate fatigue crack growth in a 3D plate. The dimension of the plate was restricted due to the maximum number of elements. This implied that the distance between the source and the receiving transducer had to be reduced making it difficult to separate the different modes. By using two monitoring nodes at the same distance but on opposite sides of the plate and by adding and subtracting the signals from them, it is possible to distinguish between symmetric S_0 and anti-symmetric A_0 waves effectively.

A three-dimensional 125 x 250 mm plate model using four elements through the thickness with element size of 0.75mm was created. The model simulates fatigue crack growth in a 3D plate with an existing pre-crack (free surface) from the right side of the plate as shown in figure 8.

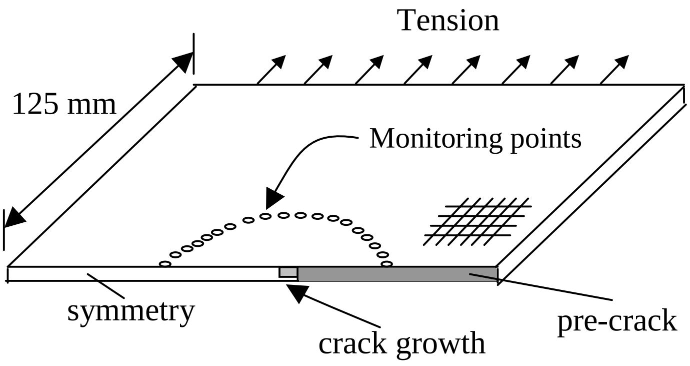


Figure 8. 3D plate model used to simulate acoustic wave from crack length growth with pre-crack.

Static load was first applied to the *ABAQUS*/Standard model. Then, nodes were released and the acoustic wave from the fatigue crack face was simulated in *ABAQUS*/Explicit model. The amplitude of the wave modes at different angles was investigated. A 3 mm long fatigue crack growth with different crack depths of 7.5 mm, 1.5 mm and 2.25 mm through the thickness in the centre of the plate were simulated. The received AE signals from the top and bottom were filtered. The added and subtracted signals produced S_0 and A_0 modes respectively as shown in figure 9.

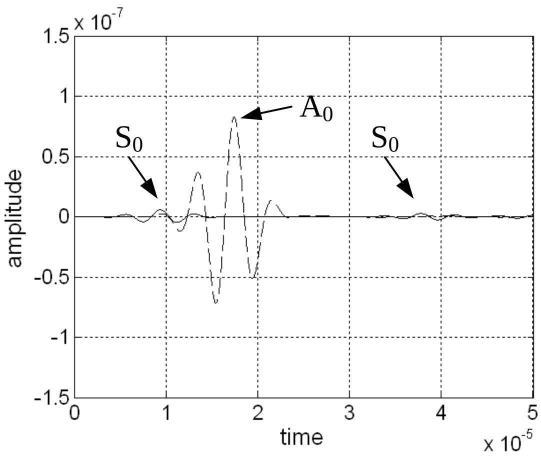
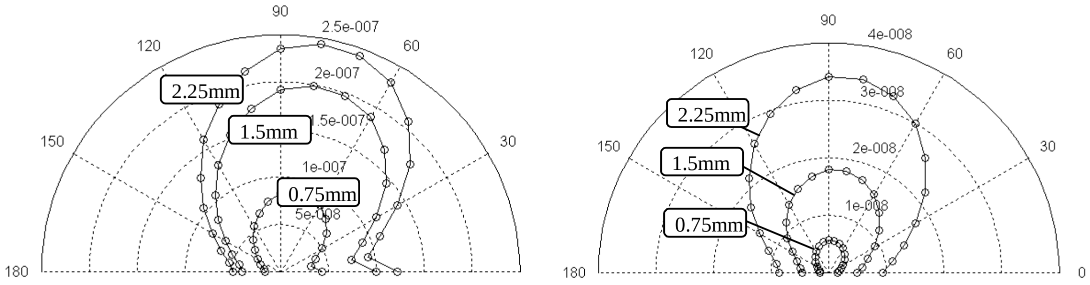


Figure 9. Added and subtracted signal showing the separated S_0 and A_0 modes

The amplitude of the individual modes was collected from different angles. The results, in figure 10, show a polar plot of the angular pattern of the A_0 and S_0 mode. A radiated pattern was obtained where the highest amplitude of A_0 was skewed toward the pre-crack and the S_0 was skewed slightly. The sharp increases in the amplitude of the A_0 mode at 0° are due to an edge wave mode propagating along the existing pre-crack.



(a) (b)

Figure 10. A polar plot showing the radiated angular mode is skewed toward the pre-crack edge: (a) A_0 mode and (b) S_0 mode

Conclusion

The experimental work showed that the acoustic waves from fatigue crack growth propagate as guided waves. Using a large plate allowed the individual wave modes to be separated in time and to be characterized. The use of 2D FE modelling to examine the effects of crack depth, indicate that for crack growths up to 86 % of the plate thickness, the A_0 mode signal has larger amplitude than the S_0 mode signal. Above 86 % the amplitude of the A_0 mode drops rapidly and the S_0 mode becomes larger. This is consistent with experimental measurements. 3D models have examined radial patterns from fatigue cracks for crack growth with a pre-crack. The difference in the depth of crack growth has an effect on the amplitude of the wave modes but does not significantly alter the angular radiation pattern. The presence of a pre-crack skews the main lobes of radiated energy toward the pre-crack.

Acknowledgement

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