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A New Approach for Fatigue Crack Length Estimation Using the Acoustic Emission Technique in Structural Health Monitoring Applications

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Abstract

The Acoustic Emission (AE) technique has been shown as capable in detecting and locating fatigue crack damage in metallic structures. However there are significantly fewer studies investigating its potential for fatigue crack length estimation. Information on the extent of crack growth would enable prediction of the remaining useful life of a component using well established fracture mechanics principles. This would improve the prospects of AE for use in structural health monitoring applications where detection and monitoring of crack lengths is required. A new approach for deducing absolute crack length has been developed based on correlations between AE signals generated during fatigue crack growth and corresponding cyclic loads. An empirical model to generate crack length was derived using AE data generated during fatigue crack growth tests in 2 mm thick SEN aluminium 2014 T6 specimens subject to a tensile stress range of 52 MPa and an R ratio of 0.1. The model was validated using AE data generated in separate tests performed with a stress range of 27 MPa. The results showed that predictions of crack lengths over a range of 10 mm to 80 mm can be obtained with the mean of the normalised absolute errors ranging between 0.28 and 0.4.

Keywords : *Acoustic Emission, Fatigue Crack, Prognostics*

Introduction

Aircraft maintenance based on the damage tolerance paradigm is underpinned by the ability to make predictions on the remaining useful life of a component using well established fracture mechanics principles relating crack length to elapsed fatigue cycles. Information on the extent of crack growth at any point in the structures operational lifetime can be related to this model and the RUL determined. Structural Health Monitoring (SHM) techniques can potentially provide continuous monitoring of such structures for the presence and severity of damage (e.g. cracks) using permanently mounted sensors. The Acoustic Emission (AE) technique can be used in performing damage detection via propagation of guided ultrasonic waves from the damage site. Its location can also be determined using time difference of arrival (TDOA) measurements of the signals detected by an array of sensors [1]. AE signals are generated during fatigue crack growth and can be classified as either primary or secondary [2, 3]. The primary sources of AE are generally associated with fracture mechanisms occurring around the crack tip which include deformation of plastic zone around the crack tip which results in local fracture of inclusions [4–6] and crack extension [4, 7, 8]. Secondary AE sources on the other hand are related to crack closure processes which results in fretting of crack surfaces [2, 8, 9]. Gagar (2013) [10] observed characteristic behaviour of AE signals generated from the various sources under constant amplitude cyclic load. It was found that the signals could be classified into distinct categories linked to the progression of a crack across a 2 mm thick sheet of aluminium and could also be associated with different AE sources.

A new approach for performing fatigue crack length estimation based on correlations between AE signals associated with crack closure during fatigue crack growth and corresponding applied cyclic

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loads is presented in this paper. An empirical model was derived using this relationship and was validated by performing crack length predictions using data sets obtained from separate tests performed on identical specimens. The novel method described in this paper produces estimates of absolute crack length in contrast to all other AE crack length estimation methods that provide only relative crack length extension and require a priori knowledge of initial crack sizes.

1. EXPERIMENTS

Fatigue crack growth tests were performed on Single Edge Notch (SEN) specimens subjected to constant amplitude fatigue loading with stress ratio (minimum load / maximum load) of 0.1 and frequency of 2 Hz. The test samples were made from 2 mm thick 2014 T6 aluminium and the dimensions were 250 mm wide, 530 mm long containing a 10 mm notch. Sample geometry is shown in Figure 1. The tests performed are summarised in Table 1. Nominally identical samples were used in the different test, made from the same material, with the same grain orientation.

Table 1 : Summary of test conditions

Number of tests	Stress range (MPa)	Stress ratio (MPa)
7	52	0.1
3	27	0.1

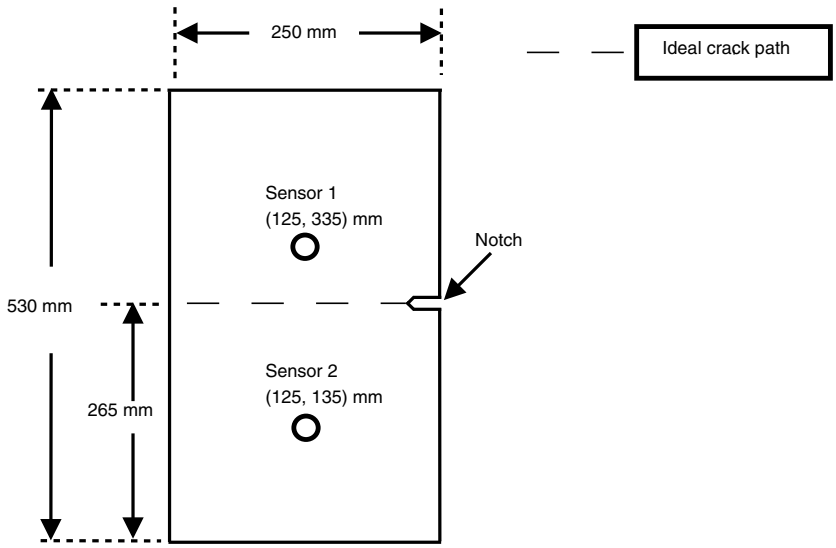

Figure 1 : Geometry of test sample and layout of AE sensors

In each of the tests conducted, a digital video system was used to monitor fatigue crack development with a specified frame capture rate. Crack lengths were measured against inscribed markings along the anticipated crack path at 1 mm intervals with an accuracy of ± 0.2 mm. Crack length data as well as corresponding fatigue cycles were recorded throughout the tests conducted.

A multi-channel Physical Acoustics AE system was used to record AE signals using broadband piezoelectric sensors with sampling rate of 1 MS/s. Preamplifier gain for each channel was set to 40 dB. Exclusive monitoring of AE signals generated from the fatigue crack was achieved by implementing a spatial filter set to ignore spurious signals generated from the test machine grips based on the Time Difference of Arrival (TDOA) measurements obtained from the detected signals. The load

output of the test machine was monitored via a ± 10V analogue input and the cyclic load values as well as number of elapsed cycles corresponding with the detected AE signals were also recorded. An association was made between the AE signals recorded during certain periods of fatigue cycles and their corresponding crack lengths.

Correlations were made between AE Hits and their corresponding values of cyclic stress at various crack lengths and their distribution represented using the Kernel Density Estimation (KDE) method [11]. This is a non-parametric method for estimating the probability density function of a random variable. It is performed in two steps as expressed in Equations (1) and (2) [11] where firstly a kernel function is assigned to each observation in the data set and then all the respective kernels are summed to obtain the density function. This was used to produce the distribution of AE Hits across the loading range at various crack lengths in the various tests conducted.

$$f(x;t) = \frac{1}{N}\sum_{i=1}^{N}\phi(x,X_i;t), x \in R \tag{1}$$

$$\phi(x,X_i;t) = \frac{1}{\sqrt{2\pi t}}e^{-\frac{(x-X_i)^2}{2t}} \tag{2}$$

Where,

ϕ - Gaussian kernel function

2. Results

The fatigue crack initiated easily from the notch root in the tests performed with stress range ($\Delta\sigma$) of 52 MPa and stress ratio of 0.1. The total fatigue lives ranged between $7.15X10^4$ and $1.14X10^5$ cycles and final failure occurred at crack lengths between 112 and 121 mm. The distribution of AE Hits with cyclic stress and crack length for two tests performed with $\Delta\sigma$ of 52 MPa are shown in Figures 2 and 3. It can be seen that although the greatest density of AE signals was produced in the lower two-thirds of the stress range. Also, it can be observed that despite both tests being conducted under nominally identical conditions there is significant variation in the distribution of AE Hits.

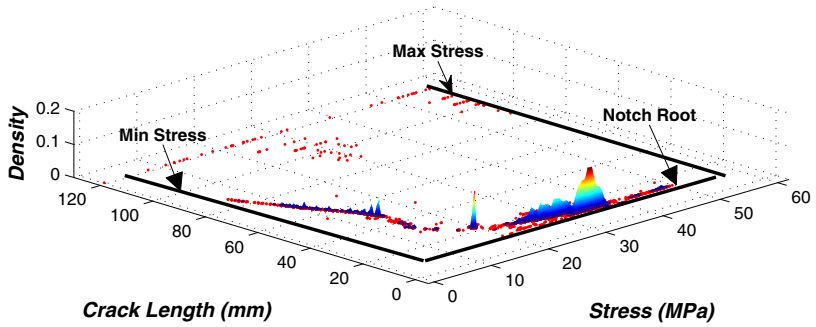

Figure 2 : AE signal distribution with cyclic stress at various crack lengths in Test 2 conducted with $\Delta\sigma$ of 52 MPa and stress ratio of 0.1

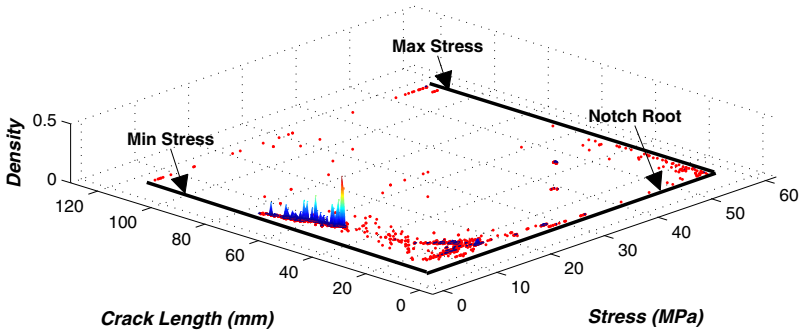

Figure 3 : AE signal distribution with cyclic stress at various crack lengths in Test 3 conducted with $\Delta\sigma$ of 52 MPa and stress ratio of 0.1

Due to the level of variation in the number of AE signals detected at various crack lengths in the seven tests performed with of 52 MPa, characteristic trends present may not be easily discernable. The distribution of the cumulative AE Hits with applied load cycles at various crack lengths in these tests was determined using the KDE method as previously described, using their cumulative data sets. The results are shown in Figure 4. It can be seen that at crack lengths from 10-20 mm (notch root at 10 mm) the greatest densities of AE signal generation were observed between 29% - 67% of the cyclic range. With subsequent crack growth beyond 20 mm the greatest densities occurred at decreasing values of the load range until a crack length of 80 mm. Also, it was observed that AE signals were generated close to the maximum stress throughout crack growth period. As the crack approached final failure AE signals began to emerge around the mean stress and at failure crack length AE signals were produced across the entire loading range. Gagar (2013) [10] showed that such trends in AE generation during fatigue crack growth are dependent on component geometry and stress ratio.

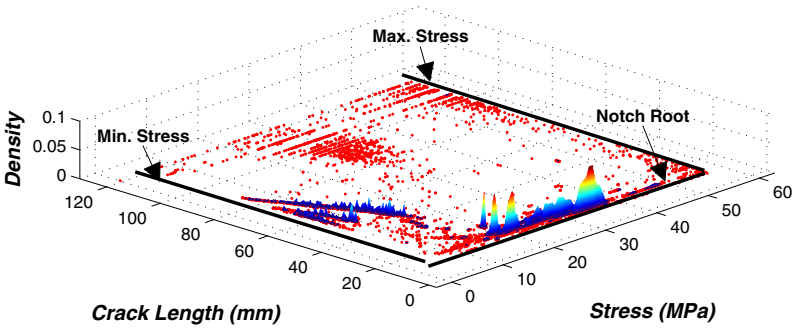

Figure 4 : Cumulative AE signal distribution with cyclic stress at various crack lengths for Tests 1 7 conducted with $\Delta\sigma$ of 52.2 MPa and stress ratio of 0.1

The results of AE signal distribution with applied load cycles at various crack lengths for the two tests performed with $\Delta\sigma$ of 27 MPa are shown in Figures 5 and 6 respectively. It can be seen that qualitatively similar behaviour as previously described for the tests performed with $\Delta\sigma$ of 52 MPa is evident.

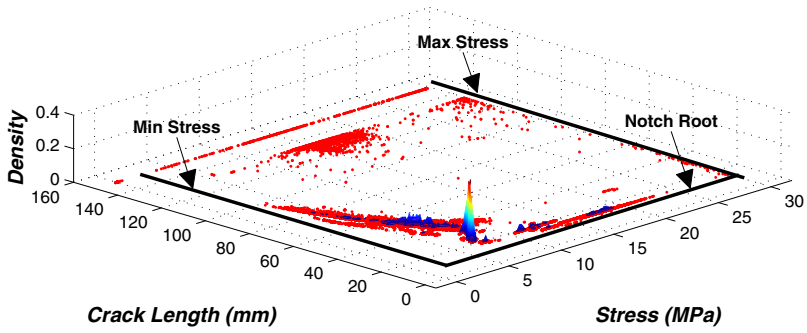

Figure 5 : AE signal distribution with cyclic stress at various crack lengths in Test 8 conducted with $\Delta\sigma$ of 27 MPa and stress ratio of 0.1

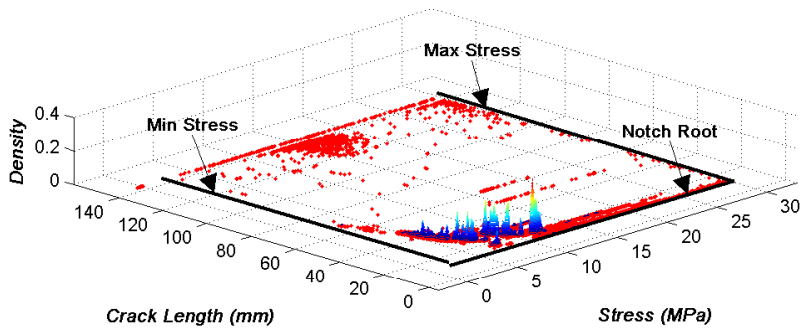

Figure 6 : AE signal distribution with cyclic stress at various crack lengths in Test 9 conducted with $\Delta\sigma$ of 27 MPa and stress ratio of 0.1

2.1 Development of crack length prediction model

The occurrence of maximum AE kernel density towards decreasing levels of applied cyclic stress as the crack grows was explored quantitatively. Figure 7 shows the averaged points in the stress range, normalised to the maximum stress, where AE signals were recorded at various crack lengths throughout Tests 1 to 7, performed with $\Delta\sigma$ of 52 MPa and stress ratio of 0.1. This diagram represents AE signals produced in the lower 70% of the stress range. An exponential best-fit model was used to characterise their relationship as also illustrated in Figure 7 and expressed in Equation 3. It can be seen that the majority of data points are located within the confidence bounds with some outliers in the period of crack growth between crack lengths of 10 15 mm.

$$f(x) = 1.7 \times exp^{-0.2\times x} + 0.4 \times exp^{-0.01\times x} \tag{3}$$

Where,

f(x) - Normalised value of stress range
x - Crack length

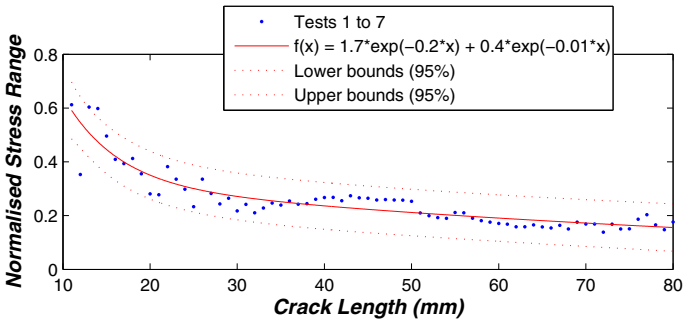

Figure 7 : Points in the normalised stress range where the mean number of AE Hits occur at various crack lengths for Tests 1 7 performed with $\Delta\sigma$ of 52 MPa and stress ratio of 0.1

2.2 Validation of crack length prediction model

Validation of the derived model was conducted using separate AE data sets recorded from Tests 8 and 9 performed with $\Delta\sigma$ of 27 MPa and stress ratio of 0.1. Figure 8 shows the averaged points in the normalised stress range where AE signals were generated at various crack lengths throughout the tests, along with the model expressed in Equation 3. It can be observed that the results also follow the exponential trend. Test 8 produced a closer fit to the model than Test 9; however the majority of data points in both tests are located within the 95% confidence limits of the model, although there were some outliers at crack lengths less than 20 mm for Test 8 and at crack lengths greater than 50 mm for Test 9. Estimates of crack length for crack growth up to 80 mm in Tests 8 and 9 were obtained using the derived model. Measurements of cyclic load values where maxima in AE signals were detected were used as input. Figure 9 shows these estimates plotted against the optically measured crack lengths where a linear trend can be seen for values of crack length greater than 30 mm. The absolute error in estimations was normalised with respect to the various measured crack lengths and results are shown in Figure 10. The arithmetic means of the normalised absolute errors obtained in Tests 8 and 9 for the entire period of crack growth were calculated to be 0.28 and 0.4 respectively, with standard deviations of 0.6 and 0.2. This suggests that the majority of crack length estimations were achieved with errors less than 28% and 40% for Tests 8 and 9 respectively.

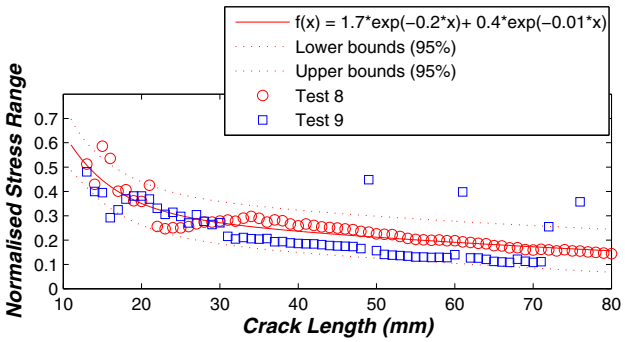

Figure 8 : Averaged and normalised cyclic stress where AE signals are generated at various crack lengths for Tests 8 9 performed with $\Delta\sigma$ of 27 MPa and stress ratio of 0.1

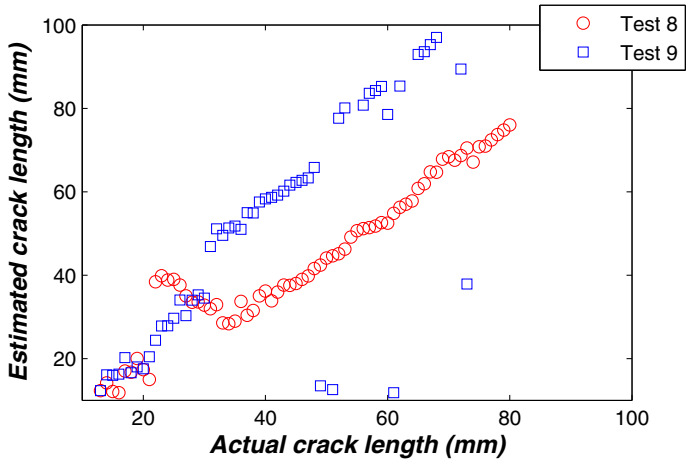

Figure 9 : Corresponding calculated versus measured crack length for Tests 8 9 performed with $\Delta\sigma$ of 27 MPa and stress ratio of 0.1 using derived model

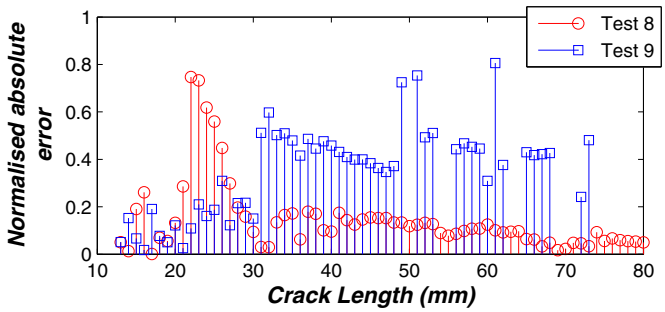

Figure 10 : Normalised absolute error in crack length predictions for Tests 8 9 performed with $\Delta\sigma$ of 27 MPa and stress ratio of 0.1

3. Discussion

The application of this approach developed is limited to crack lengths where AE signals associated with fatigue crack closure occur. As can be seen in Figures 2 to 6, this group of signals were produced for crack growth up to a crack length of 80mm. This represents approximately 99% of the sample fatigue life for this geometry and size, and predictions on the remaining useful life of the component can be made up to that point. In the context of a practical SHM application adopting a maintenance scheme based on the damage tolerant paradigm, this proportion of fatigue life would be considered adequate. The results presented in Figures 9 to 12 shows that crack length estimations can be obtained independent of the stress range applied in loading. This is evident since the model was derived using AE data generated in tests performed with $\Delta\sigma$ of 52 MPa and validated using independent AE data generated in tests performed with $\Delta\sigma$ of 27 MPa. However, Gagar [10] showed that generation of AE signals associated with crack closure exhibited different trends in cyclic loads as crack length increased with change in sample geometry. The case of a structural component subjected to variable amplitude loading would be particularly challenging for the AE signal loads-based approach in performing crack length predictions as the load cycles consist of different stress ratios and stress ranges. Although it does not appear to be sensitive to changes in stress range, it may be significantly affected by changes in stress ratio as the crack closure behaviour is less prominent or absent in certain cases. The investigation of the novel approach described here under the conditions of variable peak load amplitudes will be the subject of future research.

CONCLUSION

- A new method for estimating crack lengths in metals using acoustic emission detection has been developed by relating applied cyclic load to the AE signals generated during crack growth. Predictions can be obtained with the mean of the normalised absolute errors ranging between 0.28 and 0.4.
- This new method provides absolute values for crack lengths in contrast to other techniques that provide only relative crack extension estimates.
- The approach appears to be independent of the stress range applied in loading as a model was derived using AE data generated in tests performed with $\Delta\sigma$ of 52.2 MPa and validated using AE data generated in tests performed with $\Delta\sigma$ of 27 MPa.

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