Fatigue Crack Characterization In Epoxy L160 By Fuzzy Clustering Means On Acoustic Emission Data

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ABSTRACT

The fatigue crack growth characteristics of structural epoxy L160 are analyzed using quantitative acoustic emission (AE) technique. This was experimentally investigated by three-point bending testing of specimens under low cycle constant amplitude loading using the Fuzzy clustering Means. The crack growth sequence, that is, initiation, crack propagation, and fracture, is extracted from their corresponding frequency feature bands, respectively. The results obtained proved to be superior to qualitative AE analysis and the traditional linear elastic fracture mechanics for fatigue crack characterization in structural epoxyL160.

Key words: EpoxyL160; Acoustic Emission; Fuzzy clustering Means; Fatigue,

INTRODUCTION

Early detection of fatigue crack-growth in epoxy L160 structures is an ongoing challenge. Furthermore, characterization of the different stages of the fatigue lifecycle using NDE techniques is particularly difficult. AE systems have been shown to serve as early damage detection mechanisms in bridge structures. This technology, however, is fraught with noise problems and complex datasets that are difficult to interpret. This paper attempts to design and implement a data mining scheme that can classify raw AE datasets into discrete clusters using an improved variant of the popular Fuzzy clustering means algorithm. Linear elastic fracture mechanics (LEFM) is a useful tool for characterizing crack growth by fatigue and on other hand application of fracture mechanics to fatigue problems has become a fair routine [1]. Acoustic emission technology is the most appropriate and useful nondesyructive testing (NDT) method for studying fatigue cracks growth in civil engineering structure because it can monitor its health in real time [2]. Effective crack detection may lead to an early warning. The AE technique can be used to continuously detect slight deformation and damage in the interior of materials. In other words, sampling AE signals and analyzing their characteristics may contribute to the understanding of the real-time failure behavior of materials [3]. The AE parametric analyses have been commonly employed during fatigue crack growth characterization. Ohtsu and Tomoda [4] reported that the AE waveform shape depends on the cracking mode, enabling the classification of cracks in different materials. Shear cracks generally follow tensile as the material approaches to final failure. reported that failure phenomena in metals can be interpreted by evaluating the amplitude distribution, AE event count, and total AE energy [5]. Discussed the application of other AE parameters, such as rise angle (RA) value, rise time (RT), AE hit rate, and duration damage characterization of metal [6]. They realized that as the duration and RT increase, there is a shift of cracking mode from tensile to shear. Any articles correlated the AE parameters like rise time and duration with corrosive processes in aluminums [7].

A good correlation between AE parameters and fracture mechanics principles during fatigue has been reported by [8,9]. Grosse et al reported the pros and cons of the parametric AE analysis. They postulated that in practical applications it can be difficult to discriminate an AE signal from noise after the signal has been reduced to a few parameters.

Quantitative techniques that deal with the study of AE signal waveform have been applied in various engineering fields for damage evaluation. The fast Fourier transform (FFT) has been used to decompose a time-domain sequence in terms of a set of basic functions. A major problem in using the FFT results from the fact that the transform is the result of integration in the continuous time domain over the entire signal length [11,13]. This problem led to the evolution of the time-frequency data processing
methods, such as the short time Fourier transform (STFT). Neild et al provided a thorough review of various time-frequency techniques for structural vibration analysis. The wavelet transform which is the main interest of this paper has been successfully combined with AE signal parameter for analysis of real-time failure process, such as differentiation of crack types, quantification of damage, and identification of AE source locations [15]. This paper discusses the fatigue crack growth characterization in structural epoxyL160 and weld using quantitative methods. The frequency feature bands corresponding to crack growth sequence, that is, initiation, crack propagation, and fracture, are extracted and compared with qualitative AE analysis and LEFM.

Fuzzy clustering Means:

Fuzzy clustering technique is used to classify the AE signal to different sources of signals. FCM has the ability to discover the cluster among the data, even when the boundaries between the subgroup are overlapping. FCM based technique has an advantage over conventional statistical technique like maximum likelihood estimate, nearest neighbor classifier etc, because they are distribution free (i.e.) no knowledge is required about the distribution of data.

In the approach, the aim is of clustering is to determine the cluster centers, which are representative values of features corresponding to the classified categories. Once clustering centers are determined at the learning stage, the classification is made by the comparison of the incoming pattern and each clustering center [16].

Let \( X = \{X_1, X_2, ..., X_3\} \subset R \) where each \( X_i = (x_{i1}, x_{i2}, ..., x_{ij}) \in R \) is a feature vector; \( x_{ij} \) is the \( j \)th feature of individual \( x_i \). For each integer \( c, 2 \leq c < n \), let \( V_{cn} \) be the vector space of \( c \times n \) matrices with entries in \([0,1]\), and let \( u_{ij} \) denote the \( ij \)th element of any \( U \in V_{cn} \). The function \( u_{ij} : X \rightarrow [0,1] \) becomes a membership function and is called a fuzzy subset in \( X \). Here \( u_{ij} = u_i(x_j) \) is called the grade of membership of \( x_j \) in the fuzzy set \( U_i \). In the space of samples, we suppose that there are \( n \) samples, which can be divided into \( c \) classes. Consider the following subset of \( V_{cn} \):

\[
M_c = \{U \in V_{cn} \mid \|U\|_2 = 1, \sum_{i=1}^{c} \sum_{j=1}^{n} u_{ij} = 1, \sum_{j=1}^{n} u_{ij} \geq 0 \}
\]

Each \( U \in M_c \) is called a fuzzy c-partition of \( X \); \( M_c \) is the fuzzy c-partition space associated with \( X \). For any real number \( m \in [1,6] \), define the real-valued functional \( J : M_c \times L_c \rightarrow \mathbb{R} \) by

\[
J(U,V) = \sum_{k=1}^{c} \sum_{i=1}^{n} (u_{ik})^m \|X_k - U_i\|^2
\]

\( 1 \leq M < \infty \), and usually \( m = 2 \) where \( U = \{u_{ik}\} \) is the membership function, with \( u_{ik} \in [0,1] \), which denotes the degree of membership of the \( k \)th pattern and \( i \)th cluster centers; \( V = \{v_1, v_2, ..., v_c\} \) is a vector of c cluster. These \( v_i \) are interpreted as clusters defined by their companion U matrix, and play a functional role in our development. The functional \( J \) is a weighted, least squares objective function. In order to obtain the optimum fuzzy partition, this objective function must be minimized.

Experimental Details:

- Specimens Design:

Received epoxyL160 was supplied in the standard thermo mechanical heat treatment condition in the form of 16mm thickness plates. The standard three-point bending specimens were designed from the epoxy, as a representative part of a epoxyL160 bridge in accordance with ASTM E647 standards. The mechanical properties of the specimens used are shown in Tables 1, respectively. The specimens were notchted using electrical discharge machining (EDM) to an initial crack length of 0.6mm. The specimen was fatigue pre cracked using the MTS machine at a frequency of 1Hz of length 0.6 mm. The specimens’ surfaces were mechanically polished by grinding and buffing to permit observations of the crack path. The detailed geometry of the specimen is illustrated in Figure 1.

<table>
<thead>
<tr>
<th>Table 1: Mechanical property of epoxy</th>
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<tr>
<td>Resin</td>
<td>Density (g/cm³)</td>
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<tr>
<td>EpoxyL160</td>
<td>2.6</td>
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</table>
Mechanical testing and equipment:

A servo hydraulic testing machine with a maximum load capacity of 250 kN (Hiwa Co., Tehran, Iran) was used for the fatigue tests at an ambient temperature of 300 K. The specimens were tested under sinusoidal cyclic loading at a frequency of 7.5 Hz. The specimens were tested with different peak loads (16 kN and 10 kN) at a load R-ratios of 0.1. At least three specimens were tested under each condition in order to ensure regularity in the experiment. Damage initiation and progress in the specimens monitored by an AE system. Preliminary to damage check, the data acquisition system calibrated for each kind of specimens, according to a pencil lead break procedure. At the same time, velocity and attenuation of the AE waves can measure. For that, the lead breakage operation was repeated several times and at different locations between the sensors. The difference in arrival times on the sensors deduced. Furthermore, each waveform digitized and stored. After storage and before processing, the signals subjected to a linear location procedure to determine the location of the AE source.

The AE signals were detected by using 2 broadband piezoelectric sensors with frequency range of 10 kHz to 2 MHz. Vaseline was used at the interface between the sensors and the specimen surface to obtain proper signals. A preamplifier of 40 db gain was used to capture the AE signals. The crack-tip opening-displacement gauge (CTOD) was used to monitor the fatigue crack growth in the structure.

Results and Discussions

- Linear Elastic Fracture Mechanics:

Discovered the power-law relationship for the fatigue crack growth and proposed an exponent of 4 for the constant after series of experiments. Figures 2 and 3 respectively, shows the relationship between the fatigue crack growth rates and stress intensity factor ranges and crack length and number of cycles under different load ratios.
In nearly the whole fatigue lives, we obeyed the Paris law (7) for the epoxyL160 where is a representative crack length, is the number of fatigue cycles, is the applied stress intensity factor range, and assumed to be constants for a particular material. However, the crack growth rates were increased in the weld relative to in the base metal, suggesting that the cracks propagated more rapidly in the weld due to the changes in the microstructure. We realized from the diagram that peak load was less significant on the crack propagation rate.

- Acoustic Emission during Fatigue Crack Propagation:

The fatigue crack growth characteristics can be analyzed by studying the parameters of the AE signals so generated. Figure 4 shows the relationships between the cumulative AE counts rates and stress intensity factor ranges for the welded specimens under different peak loads. The AE counts rates increased in a linear relationship with the increase in on the log-log axes, which is well consistent. Compared to the results from LEFM, the peak load had influence on the welded specimen. Moreover, higher AE counts rates were also observed in the welded specimens than in the base metal specimens. In addition, the slopes of the lines for the welded specimens were somehow higher than the base metal specimens, also suggesting that the weld generated more AE signals during fatigue crack propagation.
**FCM Packet Analysis:**

The characteristics of fatigue crack propagation during the three-point bending testing of the epoxyL160 beam are classified under 3 stages: crack initiation, crack propagation, and failure at various peak loads corresponding to regions I, II, and III, respectively.

Figures 5 show the AE wave in region 1 which corresponds to fatigue source initiation for epoxy. The waveform is low amplitude, wide pulse with a narrow frequency scale, mostly located at 80 kHz to 180 kHz. At this stage, the AE signals are generated by the formation of crack source and plastic deformation on the tip of the notch which generate intense AE events. Higher amplitudes are recorded for epoxyL160 due to the release of residual stresses. Figures 6 show the AE in region 2 corresponding to fatigue crack propagation. The waveform at this stage as compared to the fatigue source has high amplitude, narrow pulse, with a wide energy scale, and a main frequency scale of 250 kHz to 350 kHz for the epoxy.

**Fig. 5:** Fatigue crack initiation in epoxy

**Fig. 6:** Fatigue crack propagation in epoxy

Figure 7 show the AE waveform at the rapid crack propagation stage; the energy of the AE signal increased until the specimen completely failed, and the AE waveform amplitude is higher than those of the earlier stages. The waveform characteristic shows that this type of AE signal is a burst signal. The fracture waveform is a high amplitude narrow pulse, with a wide energy scale, and a main frequency scale of 300 kHz to 400 kHz for the epoxy.
Conclusion:

From the above discussions, it is evident that fatigue crack growth rates for the welded specimen are higher than the base metal; this was enhanced by the presence of inclusions and heterogeneous microstructure of the welds. The effect of peak load on fatigue characterization was found to be insignificant. Furthermore, the quantitative technique of the wavelet transform provided clear results for crack propagation characterization in both the epoxyL160 and welded specimen.

References

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