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PREDICTING THE RATE OF FATIGUE CRACK PROPAGATION IN CONCRETE USING ACOUSTIC EMISSION

RADHIKA V.* AND J. M. CHANDRA KISHEN†

*Indian Institute of Science Bangalore, India
e-mail: radhikav@iisc.ac.in

†Indian Institute of Science Bangalore, India
e-mail: chandrak@iisc.ac.in

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Abstract. Acoustic emission (AE) is a non-destructive testing technique that can be used for real-time monitoring and quantification of fatigue crack growth in concrete structures. This can be achieved by establishing correlations between the rate of crack propagation and acoustic emission signal characteristics. The aim of the present work is to extract multiple AE parameters such as hits, counts, amplitude, and energy from AE signals and subsequently, identify the parameter that gives the best results for concrete. Based on the statistical analysis, the model incorporating AE absolute energy is found to give the most accurate estimates of crack growth rate for concrete specimens. The model is calibrated and validated by post-processing of AE data acquired during the testing of nine plain concrete beams, subjected to fatigue loading of three different frequencies.

1 Introduction

Fatigue failure stands out as a predominant mode of failure in engineering structures. It arises from the gradual buildup of damage resulting from repetitive loading, ultimately leading to the initiation and spread of both microscopic and macroscopic cracks within the material. Consequently, understanding the mechanics governing fatigue crack growth behavior becomes imperative in estimating the extent of damage and forecasting the lifespan of structures. A significant challenge in the realm of fatigue crack research lies in the assessment of crack propagation rates. Acoustic emission (AE) has emerged as a potent tool for detecting and assessing fatigue-induced damage in concrete structures. Specifically, parameters derived from the collected acoustic emission signals have been observed to demonstrate a robust correlation with fatigue crack behavior.

Harris and Dunegan [1] conducted an investigation into the interplay among crack-growth rate, cyclic stress-intensity factor, load-cycling rate, and the observed behavior of acoustic emissions. They put forth a quantitative relationship that links these variables. Roberts and Talebzadeh [2, 3] established correlations between crack propagation rates, the range of stress intensity factors, and the count rates of acoustic emissions. Zarate et al. [4] introduced deterministic and probabilistic models for predicting crack growth, exploring the impact of various uncertainties through Bayesian inference. Keshgar et al. [5] employed Bayesian regression techniques to establish a linear correlation between acoustic emission count rates and fatigue crack growth rates in both Aluminum and Titanium alloys. Notably, this developed model exhibited independence from loading ratio and loading frequency. Most of these studies have consistently identified a log-linear relationship between the rate of crack propagation and the rate of AE parameters. Following the experimental acquisition of AE data, it becomes possible to compute crack growth rates and subsequently determine crack lengths through simple integration. However, a significant challenge in this approach revolves around the selection of the appropriate AE parameter for quantitative predictions of fatigue crack growth. Among the most frequently employed AE parameters for this purpose in the literature is AE counts [2, 5–8]. It is worth noting that AE parameters are often chosen in a somewhat arbitrary manner, based on pre-existing knowledge or assumptions in each specific case [9]. To enhance the precision of crack propagation rate predictions, it becomes essential to identify the most suitable parameter tailored to the material under investigation.

Extensive research efforts documented in the literature have utilized AE as a tool to comprehend and quantify fatigue damage in both plain concrete [10–12] and reinforced concrete [13–15]. However, it's important to note that while numerous studies have explored the relationship between AE and the fatigue behavior of concrete, the models proposed in existing literature predominantly focus on predicting the fatigue life of specimens, rather than assessing their current condition. Furthermore, many of the established methods for predicting fatigue behavior in concrete rely on S-N curves of the material or require knowledge of specific loading conditions, which can often be uncertain or unavailable in practical scenarios.

In the present study, an analysis of AE data obtained from fatigue testing of plain concrete beam specimens is undertaken to investigate the potential correlation between the extracted AE parameter rate and the rate of fatigue crack growth within the stable crack propagation zone. The study also aims to evaluate and critically compare the suitability of AE parameters such as hits, counts, amplitude, and absolute energy in predicting crack growth in plain concrete. Additionally, a model is developed and validated for various loading frequencies, establishing a relationship between AE parameters and crack growth rates.

2 Experimental Program

An experimental program conducted to study behaviour of plain concrete beams under fatigue loading is considered here. The concrete mix design adheres to the Indian standard code of practice, resulting in cube compressive strength, tensile strength, and modulus of elasticity values of 38 MPa, 2.6 MPa, and 33,766 MPa, respectively. Notched beam specimens with dimensions of 680 x 150 x 50 mm and a span-to-depth ratio of 4 are meticulously prepared and tested under three-point bending. The beams are initially subjected to monotonic loading until failure. Following this, fatigue tests are conducted under a constant amplitude fatigue loading regime in load control mode. The minimum load amplitude is kept at 0.25kN to guarantee adequate contact between the loading device and the specimen, while the maximum load amplitude is held at 80% of the static peak load. These tests are conducted at three distinct loading frequencies: 0.5 Hz, 2.0 Hz, and 4.0 Hz.

The monitoring of micro and macro cracking behavior within the test specimen is conducted using the Physical Acoustic Corporation system. Six R6D type piezoelectric AE sensors are affixed to the surface using high vacuum silicon grease as a couplant. The schematic representation of the AE sensor locations, in conjunction with the beam specimen's geometry, is illustrated in Figure 1. The signals captured by these AE sensors undergo amplification through a preamplifier boasting a 40dB gain before being recorded by the data acquisition system.

In addition to AE, the Digital Image Correlation (DIC) technique is employed to monitor surface strains. This entails applying a random speckle pattern to the specimen's surface and

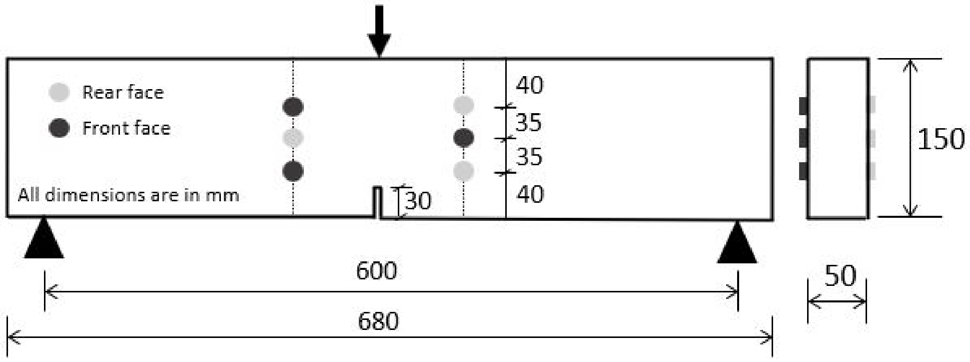


Figure 1: Typical beam specimen

capturing digital images of the deforming specimen at regular intervals. An analysis of these captured images yields insights into the variation of crack length as a function of loading. Further details regarding the experimental investigation, AE, and DIC can be found in [10] and [11].

The mechanical, acoustic, and DIC data obtained during these experiments serve as the basis for developing a theoretical model aimed at predicting fatigue crack growth in concrete, a topic explored in the following section.

3 Formulation of the theoretical model

As internal microcracks initiate and propagate, the strain energy contained within the concrete specimen is suddenly discharged in the form of elastic waves, giving rise to acoustic emissions. Consequently, AE signals hold valuable information pertaining to the progression of internal damage and fracture during the process of deformation and failure [16]. To further analyze these AE signals, essential parameters such as amplitude, counts, and absolute energy for each AE hit are extracted from the raw data file. In this study, AE data from nine specimens are considered, with three specimens subjected to each of the loading frequencies: 0.5 Hz, 2.0 Hz, and 4.0 Hz.

The relationship between crack length and the number of cycles, as determined using DIC, is directly sourced from the work of Keerthana and Kishen [11]. It's important to highlight that the literature has extensively explored the correlation between fatigue crack growth rates and the rate of growth in acoustic emission parameters across various materials, including metals, alloys, and composites. The methodology commonly found in the literature relies predominantly on the Paris law, which formulates the rate of fatigue crack propagation ($\frac{da}{dN}$) as a function of the stress intensity factor (ΔK) within the stable crack growth region and is written in a log-log form as given below [17]:

$$log\left(\frac{da}{dN}\right) = a_1 + a_2\, log(\Delta K) \qquad (1)$$

where a is the crack length; N is the number of loading cycles; a_1 and a_2 are material dependent constants.

A similar relation has been proposed in the literature establishing a connection between the rate of AE parameter, $\frac{dp}{dN}$, and the stress intensity factor, ΔK as given below [8]:

$$log\left(\frac{dp}{dN}\right) = b_1 + b_2\, log(\Delta K) \qquad (2)$$

Here, p is the AE parameter such as cumulative hits, counts, amplitude or absolute energy and b_1 and b_2 are constants. By merging Equations 1 and 2, it becomes evident that there exists an empirical log-linear relationship between the rate of fatigue crack growth and the rate of AE parameter change. This relationship can be articulated as follows:

$$log\left(\frac{da}{dN}\right) = \alpha_1 + \alpha_2\, log\left(\frac{dp}{dN}\right) \qquad (3)$$

where α_1 and α_2 are experimentally determined constants. To facilitate a meaningful comparison of correlations derived from data under various loading conditions and geometries, the crack length in the current study is normalised with respect to the beam's depth, denoted as b. Consequently, da/dN, is the rate of change in relative crack length, a/b.

The choice of the appropriate AE parameter for inclusion in this model is of paramount importance in ensuring the accurate assessment of fatigue crack growth rate. Instead of arbitrarily selecting an AE parameter, this study aims to pinpoint the parameter that yields the most accurate results for concrete. Four distinct AE parameters—cumulative hits, counts, amplitude, and absolute energy—are taken into consideration, and their rates of change with loading cycles are systematically computed at regular intervals over the course of fatigue life. Figure 2 illustrates the typical correlation between the rates of AE parameters and the rate of fatigue crack growth on a log-log scale. The experimentally observed linear trend for the stable crack growth segment affirms the applicability of the empirical relationship proposed in Equation 3 to concrete as well.

In order to quantitatively assess the effectiveness of different parameters in characterizing the relationship between acoustic emission and crack growth, linear least square regressions are conducted for each specimen. This analysis helps identify the model that most accurately represents the collected data. The evaluation of these models is based on the coefficient of determination, denoted as R^2, which is a statistical measure indicating the degree to which the data aligns with the proposed model. Table 1 compiles the R^2 values for all specimens, alongside the mean and coefficient of variance (CV). CV, calculated as the ratio of the standard deviation to the mean and expressed as a percentage, is a common metric used to assess the dispersion of data points around the mean.

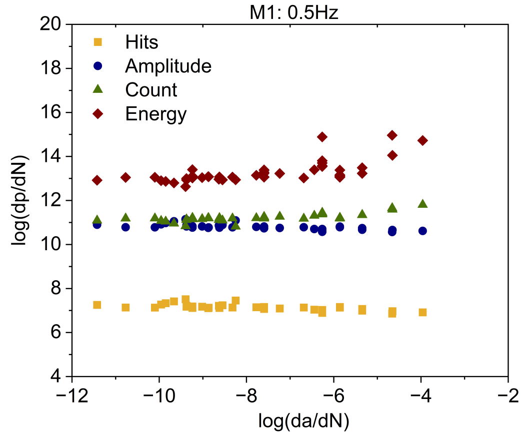


Figure 2: Typical correlation between AE parameter rate and crack growth rate on log-log scale

The goodness of the fit varies according to the AE parameters employed, as depicted in Table 1. Among the parameters under consideration, the regression model based on AE count exhibits the highest R^2 value (0.51), albeit with a relatively high CV value of 42.03%. Absolute energy, on the other hand, records the second highest R^2 value and a considerably lower CV value of 15.83%, making it a more favorable choice compared to other parameters. Both hit and amplitude exhibit relatively lower R^2 values and elevated CV values, rendering them unsuitable for the formulation of the proposed model. Despite the highest R^2 value being associated with counts, absolute energy, with its reasonably high R^2 and the lowest CV value, emerges as the more preferable option for predicting fatigue crack propagation in concrete. This preference for AE energy over count is reinforced by the fact that AE count calculation is highly dependent on the chosen threshold value, whereas AE energy is less affected by it. Nevertheless, AE count can still be considered a viable alternative for model formulation. It's worth noting that, for a highly heterogeneous material like concrete, the observed range of R^2 values can be deemed reasonable.

Table 1: Goodness of fit (R^2) for correlation between AE parameter rate and crack growth rate

AE Parameter	R^2									Mean	CV
	0.5 Hz			2.0 Hz			4.0 Hz				
	M1	M2	M3	M1	M2	M3	M1	M2	M3		(%)
Hits	0.36	0.03	0.07	0.65	0.23	0.06	0.51	0.14	0.33	0.26	82.50
Amplitude	0.32	0.30	0.11	0.69	0.25	0.05	0.66	0.03	0.50	0.32	76.97
Counts	0.45	0.53	0.13	0.79	0.63	0.43	0.28	0.63	0.75	0.51	42.03
Absolute energy	0.41	0.63	0.52	0.55	0.42	0.55	0.42	0.57	0.45	0.50	15.83

Out of the nine specimens considered in the study, six specimens (M1 and M3 of each loading frequency) are used for calibration and three specimens (M2 of each loading frequency) are used for validation of the model. The calibrated values of the material constants in the model are given below:

$\alpha_1 = -24.195$
$\alpha_2 = 1.190$

4 Validation of the model

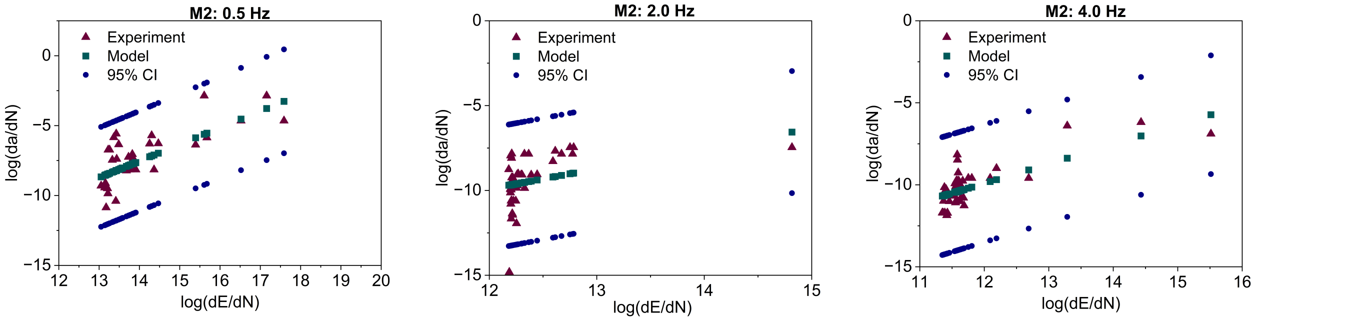
After estimating the model parameters, the fatigue crack propagation rates for any given specimen can be obtained through post-processing of the observed AE data. This proposed model is then applied to all specimens, and the typical log-log plots of fatigue crack growth rate and absolute energy rate are presented in Figure 3. For each value of the independent variable ($\frac{dE}{dN}$), both the mean and the 95% confidence intervals (CI) for the dependent variable ($\frac{da}{dN}$) are plotted. The analysis reveals that 95.5%, 100%, and 89.4% of the predicted values fall within the 95% CI intervals for specimens subjected to loading frequencies of 0.5, 2.0, and 4.0 Hz, respectively.

After acquiring the crack propagation rate, it becomes possible to calculate the crack lengths by performing numerical integration starting from an initial known crack length. Figure 4 presents the model's predictions of relative crack length (a/b), alongside the experimental crack length curve for specimens subjected to varying frequencies. In this context, the mean absolute percentage error (MAPE) serves as a statistical metric to measure the degree of alignment between the model's predictions and the actual experimental crack length values. MAPE is defined as follows [18]:

$$MAPE = 100 * \frac{1}{n} \sum_{t=1}^{n} \left| \frac{A_t - F_t}{A_t} \right| \quad (4)$$

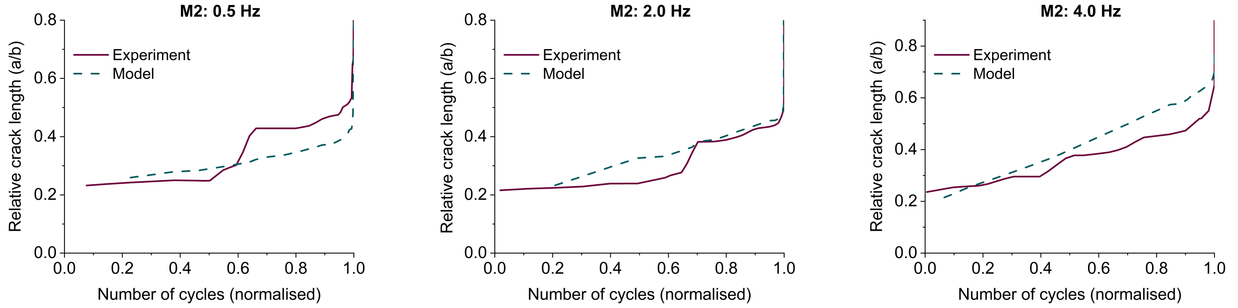
where A_t and F_t denote the actual and predicted values at data point t and n is the number of data points. The predictive distribution of crack size for the specimens subjected to 0.5, 2.0, and 4.0 Hz agrees well with the actual crack size computed from DIC, with the MAPE being 17.32%, 7.94% and 15.93%, respectively. It's important to highlight that, on the whole, the MAPE for all specimens remains under 18%, a level of accuracy that can be considered acceptable, particularly considering the markedly heterogeneous composition of concrete.

One notable benefit of this model is its ability to estimate crack propagation rates without requiring prior knowledge of crack length or the number of load cycles. Moreover, it can effectively account for the influence of the heterogeneous nature of concrete. Even when two identical specimens are subjected to identical loading conditions, their fatigue behavior is affected by the unique internal structure of each specimen. Unlike mathematical models described in the literature, which rely on input parameters like specimen geometry, material properties, or loading configurations and thus cannot address these disparities, acoustic emission captures the true internal configuration of each specimen. Consequently, it can accurately predict the individual fatigue response for each specimen.



(a) (b) (c)

Figure 3: Comparison between predicted and experimental crack growth rates



(a) (b) (c)

Figure 4: Comparison between predicted and experimental crack length

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