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EFFECT OF LOADING FREQUENCY ON FLEXURAL FATIGUE BEHAVIOUR OF CONCRETE

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Abstract. Frequency of loading plays a signicant role in influencing the fatigue response of concrete. It is widely accepted in the literature that concrete fatigue life increases with increase in loading frequency. This behaviour is counter-intuitive, as the specimen is expected to fail in less number of cycles when subjected to higher loading frequency. This paper aims at understanding the fracture and failure mechanisms responsible for this counter intuitive behaviour through an experimental investigation. The flexural fatigue experiments are performed on concrete beam specimens subjected to three different loading frequencies: 0.5 Hz, 2 Hz and 4 Hz with the aid of acoustic emission technique. The mechanical and acoustic emission results reveal that the increased fatigue life for specimens subjected to higher loading frequencies is attributed to the widely distributed and randomly oriented micro cracks that can blunt the effect of high stresses by increasing the energy required to cause failure. The concrete specimens subjected to lower loading frequencies tend to exhibit brittle behaviour and consequently fail at lower number of fatigue load cycles.

1 INTRODUCTION

Fatigue behaviour of concrete is influenced by various factors such as stress range, stress ratio, size, material strength and loading frequency. Over the years, a lot of research has been devoted to study the influence of each of these parameters on fatigue life of concrete [1–11]. Primarily, the experiments are performed to generate a S-N curve, which gives the relation between the applied stress (S) and fatigue life (N). Furthermore, several empirical and analytical fatigue models, based on mechanistic approaches are proposed in the literature which focuses mainly on the effect of size, stress ratio and stress range. While several researchers have investigated the effect of loading frequency experimentally, very few [7–9, 11, 21], have considered its effect through analytical models due to the complexities involved. The early experimental works reported in the literature on the effect of loading frequency on compressive or tensile or flexural fatigue behaviour of concrete [2, 5, 11] show a general trend of increase in fatigue life with increase in loading frequency. The fatigue models have evolved by including a frequency parameter illustrating this trend. Hsu [7] was the first to introduce the effect of frequency (f) in a fatigue equation by modifying classical fatigue equation put forward by Aas and Jackson [12]. Another model was proposed by Zhang et al. [8] in which they considered the effect of loading frequency in addition to stress reversal. Saucedo et al. [9] proposed a probabilistic fatigue model applied to concrete cubic specimens under compressive fatigue loading by considering the effect of load ratio and frequency. The model is based on the initial probabilistic distribution of static strength of concrete and it requires two series of tests at different frequencies to fit its parameters. This model was further validated for flexural fatigue tests by Rios et al. [15]. Being a statistical model, it is efficient in predicting the fatigue life of concrete subjected to compressive, tensile or flexural fatigue loading.

Though the proposed fatigue models with the integration of frequency parameter are successful in illustrating the trend of increase in fatigue life with increase in frequency, the mechanics behind such counter intuitive behaviour is not explained in any of the previous work. Most of the proposed models correlate the increased fatigue life with frequency with the dynamic strength of concrete [9, 15]. Since the static strength of concrete is significantly influenced by rate of loading [16, 17], the fatigue performance is anticipated to be affected by this parameter. Concrete being a highly heterogeneous material, the micro structural characteristics strongly influences the global response and its material properties. The fracture and failure mechanisms of concrete and its sensitivity towards loading frequency can be understood by investigating the material response at micro scale. The acoustic emission technique [13, 14] is an efficient tool to investigate the micro and macro mechanisms occurring at the interior of the material. The main objective of the present work is to understand the mechanisms responsible for the counter intuitive behaviour of concrete showing increased fatigue life with increase in loading frequency.

In this research, the effect of loading frequency on the flexural fatigue behaviour of concrete is studied experimentally on plain concrete beam specimens subjected to three-point bending with the aid of acoustic emission (AE) technique. The AE technique efficiently captures the progression of micro structural events at interior of the specimen and hence provides a deeper insight in order to comprehend the intricate mechanisms. The work presented in this paper is structured as follows: The experimental program detailing the materials used for specimen preparation and the test set-up are described in Section 2. The results of mechanical tests and AE emission are discussed in Section 3 and Section 4, respectively. Finally, Section 5 presents the main conclusions drawn from the present work.

2 EXPERIMENTAL PROGRAM

2.1 Materials and test specimen used

The concrete mix is prepared with a targeted cube compressive strength of 38 MPa according to IS codal provision. The mix proportion details and properties of various ingredients used in the preparation of concrete, are summarized in Table 1. The beam specimens are prepared by pouring the freshly mixed concrete into the wooden moulds. The specimens are demoulded after one day of casting and kept in water tanks for curing. The beams are of dimension 680 x 150 x 50 mm, spanning 600 mm from either supports. A notch of 2 mm width and 30 mm depth is introduced in the specimens at the time of casting. In addition to concrete beam specimens, standard cubes and cylinders are prepared to determine the elastic properties of the material.

2.2 Experimental set-up and loading details

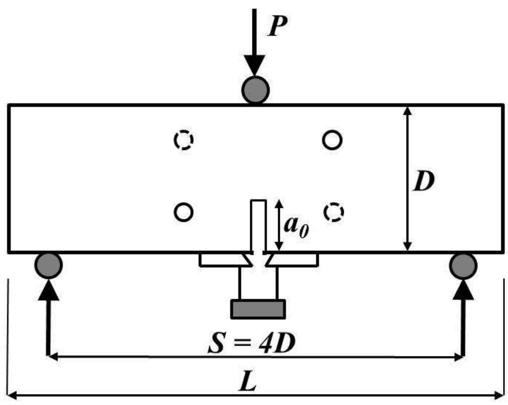


Figure 1: Schematic diagram of test set-up

The concrete beam specimens are tested under three-point bending in a closed loop servo-

Table 1: Details of concrete mix and material properties

Type of cement	:	OPC 53
Type of fine aggregates(F.A)	:	River sand
Size of F.A	:	Passing through sieve 4.75mm
Specific gravity of F.A	:	2.67
Type of coarse aggregates$(C.A)$	:	Crushed granite stones (angular)
Maximum size of C.A	:	12.5mm
Specific gravity of C.A	:	2.74
water/cement ratio (w/c)	:	0.54
Mix proportion $(C : FA : CA)$	:	1 : 2.3 : 3
Compressive strength (f_{ck})	:	38 MPa
Tensile strength (f_t)	:	2.6 MPa
Poisson's ratio (ν)	:	0.12
Modulus of Elasticity (E)	:	33766 MPa

controlled testing machine having a capacity of 35 kN. The crack mouth opening displacement (CMOD) is measured using a clip gage mounted across the notch and load point vertical displacement is measured using linear variable differential transformer (LVDT) mounted at the mid-span of the beam. The schematic diagram of beam under three point bending is shown in Figure 1. The beam specimens are initially tested under CMOD control with a loading rate of 0.001 mm/sec to obtain the peak load and the post peak behaviour. Subsequently, the specimens are tested under constant amplitude fatigue loading with a sinusoidal waveform at three different frequencies of 0.5 Hz, 2 Hz and 4 Hz. The minimum load amplitude is maintained at 0.25 kN to ensure sufficient contact between the specimen and the loading device. The maximum load amplitude is kept at 80% of static peak load. The data of load, CMOD, load point displacement and time are acquired simultaneously through a data acquisition system.

An acoustic emission (AE) system is set up to acquire data as a result of micro cracking inside the specimen when the mechanical test is in progress. Six AE sensors are attached to the specimen to obtain three-dimensional location of AE events. The AE data such as number of hits, number of events, number of counts, energy, spatial positions, amplitude and time are simultaneously acquired during the experiments using a separate data acquisition system. In order to filter the background noise, a threshold value of 35 dB is adopted. AE sensor, R6D which is a resonant type differential sensor with a operating frequency varying from 35 to 100 kHz is used in the present work. To ensure perfect contact between the specimen surface and AE sensor, high vacuum silicon grease is used as a couplant. AE signals received from the sensors are amplified with a gain of 40 dB using pre-amplifiers and sent to data acquisition system. A schematic diagram of acoustic emission system is shown in Figure 2.

3 DISCUSSION OF MECHANICAL TEST RESULTS

Three specimens are tested under monotonic loading for which an average peak load of 3.35 kN with a standard deviation of 0.078 kN is obtained. The fatigue experiments with particular frequency are performed on the beam specimens until a minimum of three consistent values of fatigue life falling in an acceptable band is obtained. The fatigue life of specimens subjected to loading frequencies 0.5 Hz, 2 Hz and 4 Hz are shown in Table 2. The counter intuitive trend of increase in fatigue life with increase in frequency is clearly observed from the values of fatigue life presented in Table 2. The variation of stiffness computed as the unloading slope at each fatigue cycle of load-CMOD curve is plotted against number of loading cycles as shown in Figure 3(a)-(c). Each figure shows stiffness

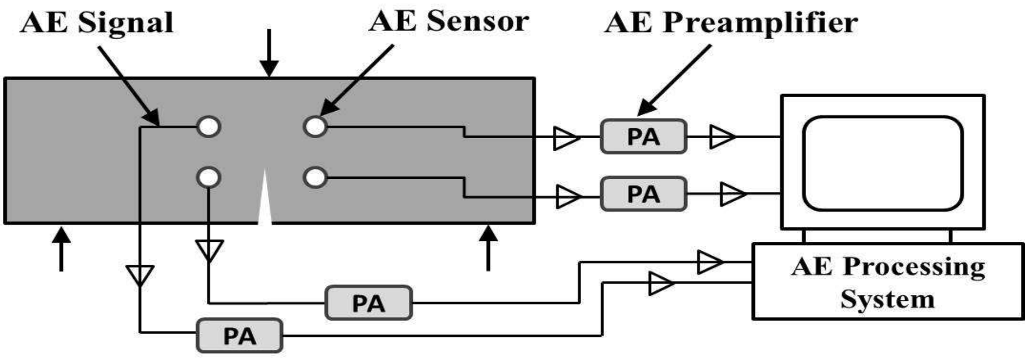
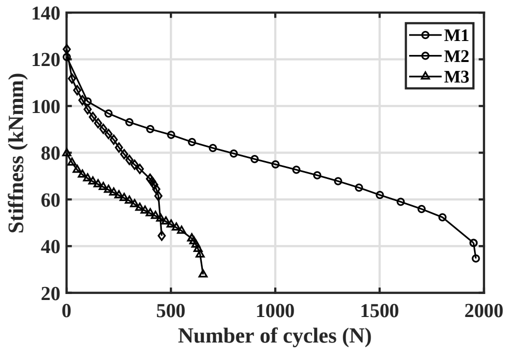


Figure 2: Acoustic emission system schematic diagram

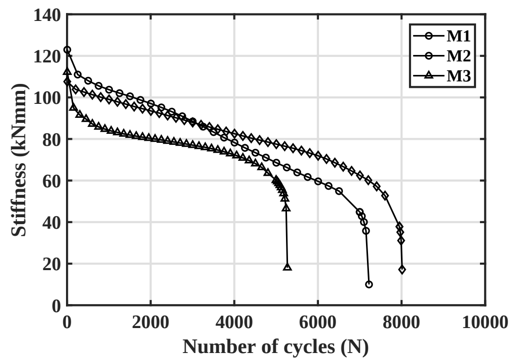
Table 2: Fatigue life for concrete specimens (in cycles) subjected to fatigue loading

Specimen No.	N_f		
	0.5Hz	2Hz	4Hz
1	460	7223	16668
2	657	5270	20777
3	1964	8089	27440
4	-	356	2924262
5	-	42286	-

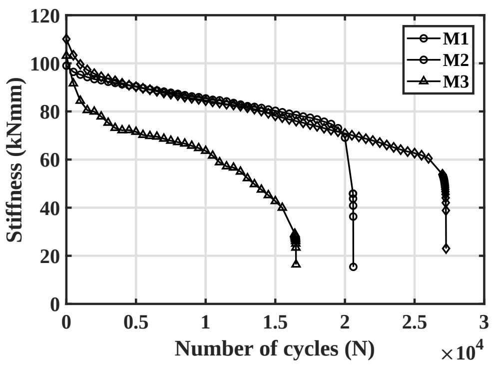
degradation of three specimens subjected to a particular frequency. We observe three phases in stiffness degradation for all the three figures irrespective of variation in the applied frequency. The first phase falls within initial 10% of fatigue life (N_f). The voids, pores and micro cracks present in the pristine state of the material gets consolidated in this phase which is followed by stable decrease in stiffness in the second phase. The stable decrease in stiffness is attributed to progressive damage in the material due to initiation of micro cracks and propagation of pre-existing cracks. This is a dominant phase spanning from 10% to 90% of fatigue life. The final phase shows an unstable decrease in the stiffness which is attribute to coalescence of micro cracks to form macro cracks leading to sudden failure at final load cycle. Furthermore, we observe that the slope of the second phase is much steeper for specimens subjected to 0.5 Hz frequency indicating higher rate of stiffness degradation in each cycle.



(a) 0.5 Hz



(b) 2 Hz



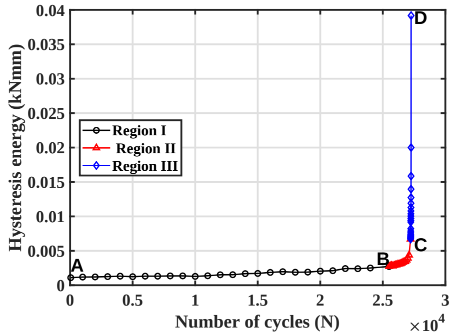
(c) 4 Hz

Figure 3: Degradation of stiffness with fatigue loading cycles

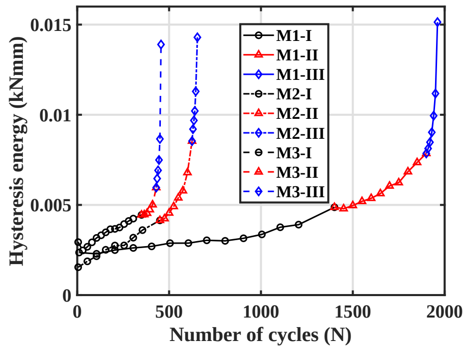
The variation of hysteresis energy dissipated per cycle is shown in Figure 4(a)-(d) with Figure 4(a) illustrating a typical curve with markings A, B, C and D for explanation purpose and Figure 4(b)-(d) for loading of frequencies 0.5 Hz, 2 Hz and 4 Hz respectively. The hysteresis energy curve for each specimen could be divided into three regions. The first region begins from the first cycle until the cycle where stable increase in hysteresis energy is observed, which is denoted by points A to B in Figure 4(a). The second region is between points B and C where the slope of curve increases at a faster rate and finally, the third region from point C to D where the hysteresis energy shoots up close to failure. The variation of hysteresis energy for the specimens across different frequencies are shown in Figures 4(b)-(d). We observe that specimens subjected to 2 Hz and 4 Hz frequency show slow and gradual increase in hysteresis energy in the first region whereas rate of hysteresis energy dissipation is higher for specimens subjected to 0.5 Hz.

In order to understand the behaviour of concrete specimens subjected to different frequencies, the stiffness, hysteresis energy and CMOD values corresponding to points A, B, C and D are shown in Figure 5(a)-(c) respectively for the three different frequencies considered. The following observation are made from these figures:

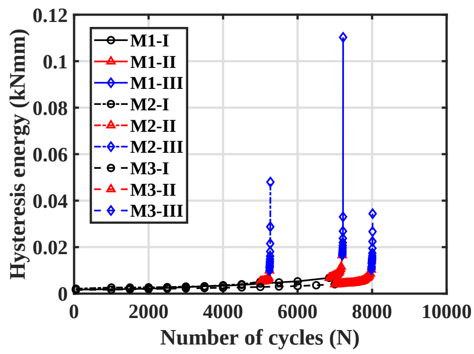
1. In Figure 5(a), the normalised stiffness values corresponding to points A, B, C and D across frequencies are shown with the normalization done with respect to the initial value of stiffness. We observe that at point A, the initial stiffness across different frequencies falls in the same range. At points B, C and D the stiffness shows a decreasing trend with increase in frequency. At failure point D, the stiffness of specimens subjected to 0.5 Hz is about 40% of its initial stiffness whereas stiffness at failure for specimens subjected to 2 Hz and 4 Hz is about 20% of its initial stiffness. The specimens subjected to 0.5 Hz fails at higher stiffness compared to



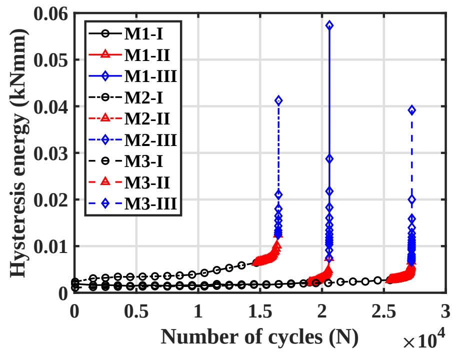
(a) Hysteresis energy



(b) 0.5 Hz



(c) 2 Hz



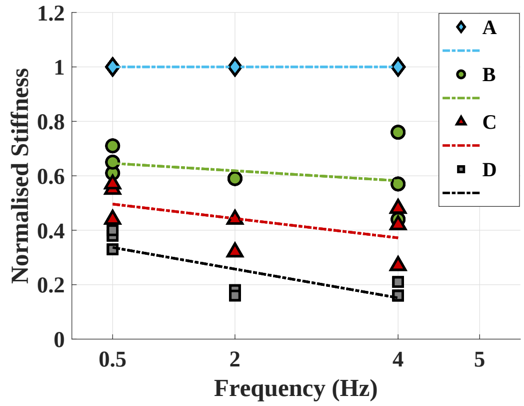
(d) 4 Hz

Figure 4: Variation of hysteresis energy with fatigue loading cycles

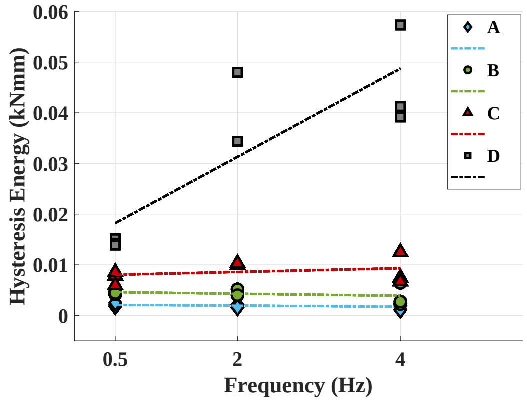
specimens subjected to frequencies of 2 Hz and 4 Hz. This implies that specimens subjected to lower frequency behave in a brittle manner.

2. The hysteresis energy values corresponding to points A, B, C and D across frequencies are shown in Figure 5(b). We observe that at point A, initial hysteresis across different frequencies falls in the same range. At points B, C and D the hysteresis energy shows an increasing trend with increase in frequency. At failure point D, we observe drastic increase in the hysteresis energy with increasing frequencies. At failure, the specimens subjected to 0.5 Hz has dissipated hysteresis energy of approximately 0.014 kNmm and for specimens subjected to 2 Hz and 4 Hz frequency, the hysteresis energy dissipated at failure is around 0.04 kN and 0.05 kNmm respectively. The higher value of hysteresis energy dissipated at failure indicates that more energy is required to break the specimen. The energy required to break the specimen subjected to 0.5 Hz frequency is less than the energy required to break specimens subjected to 2 Hz and 4 Hz. Consequently, it shows that specimens subjected to lower frequencies tend to behave in a brittle manner.

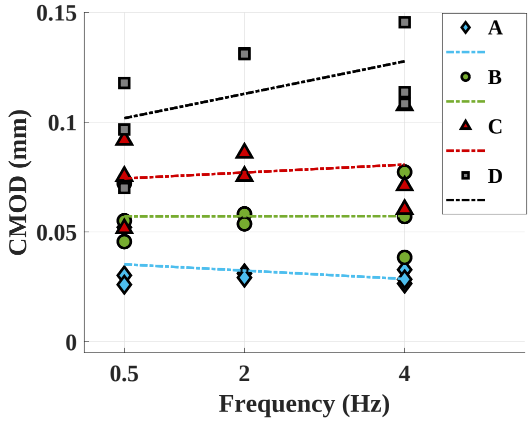
3. The CMOD values corresponding to points A, B, C and D across the three frequencies considered are shown in Figure 5(c). We observe that at points B, C and D, the CMOD values increase with increase in frequency. At failure point D, we observe that specimens subjected to 0.5 Hz frequency has failed at lower CMOD values ranging from 0.07 to 0.12 mm compared to specimens subjected 2 Hz and 4 Hz which has failed at CMOD values ranging from 0.1 to 0.15 mm.



(a) Normailised Stiffness



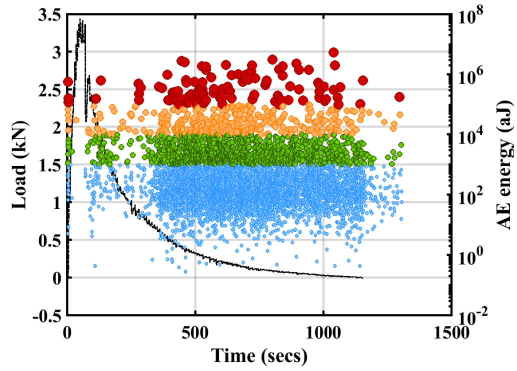
(b) Hysteresis Energy



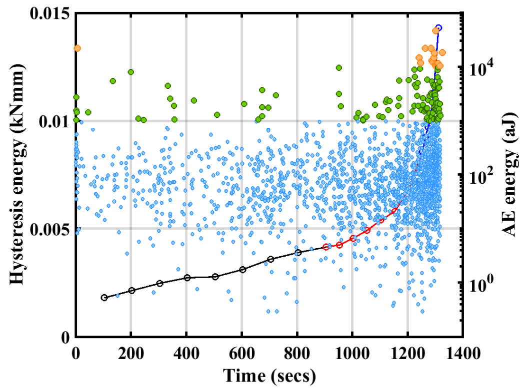
(c) CMOD

Figure 5: Variation of normalised stiffness, hysteresis energy and CMOD at points A,B,C and C for specimens subjected to different frequencies

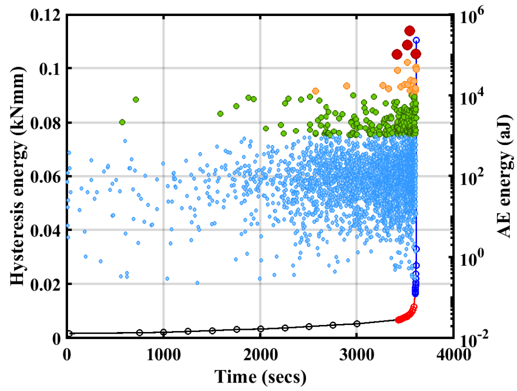
From these observation we can infer that the specimens exhibit brittle behaviour when subjected to lower frequencies. The frequency of the applied loading significantly affects the



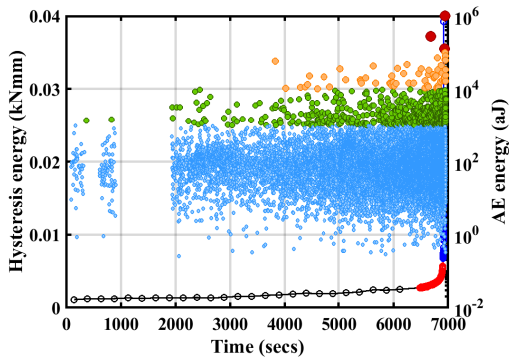
(a) Monotonic



(b) 0.5 Hz



(c) 2 Hz



(d) 4 Hz

Figure 6: Progression of hysteresis energy and AE events of varying magnitude with time

micro structure of concrete which is reflected on the concrete properties. The reason behind such observation could be understood in a better way by looking into the micro structural cracking mechanisms as revealed through acoustic emission in the following section.

4 DISCUSSION OF ACOUSTIC EMISSION RESULTS

The evolution of micro cracks in the interior of the specimen is obtained through acoustic emission results. Every AE event corresponds to a micro crack in the interior of the specimen. The AE events and the magnitude of AE energy obtained from acoustic emission signals could be attributed to different sizes of micro cracks evolved during fracture and fatigue process. The scatter and evolution of micro cracks with time for specimens subjected to monotonic and fatigue loading with frequencies 0.5 Hz, 2 Hz and 4 Hz are shown in Figure 6(a)-(d) respectively. The following observation are made from these figures:

1. Figure 6(a) shows the evolution of AE events in a specimen loaded monotonically. We observe that large number of AE events are effectively generated in the softening region of load curve. The high magnitude events have AE energy greater than 10^5 Atto Joules. The size of the markers are varied according to the magnitude of AE energy. The high AE energy events occurs due to the coalescence of micro cracks which transforms into a macro crack. The progression of AE events of varying magnitude (as shown by markers of different sizes) occurs simultaneously indicating formation of micro cracks, their coalescence and gradual propagation of macro crack in the softening region until failure.

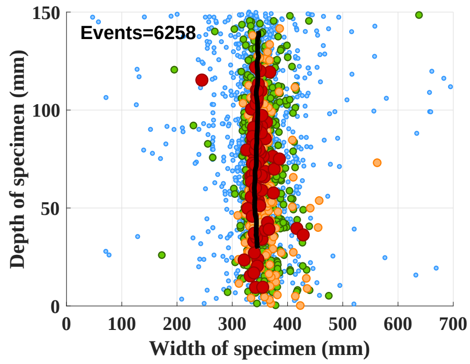
2. Figure 6(b)-(d) shows the evolution of AE events of varying magnitude for specimens subjected to fatigue loading with

frequencies 0.5 Hz, 2 Hz and 4 Hz respectively. For the specimens loaded under fatigue, the general fracture behaviour is similar irrespective of applied frequency. Micro cracks occur for the dominant period of fatigue life which subsequently coalesce at the end of the fatigue life and leading to failure.

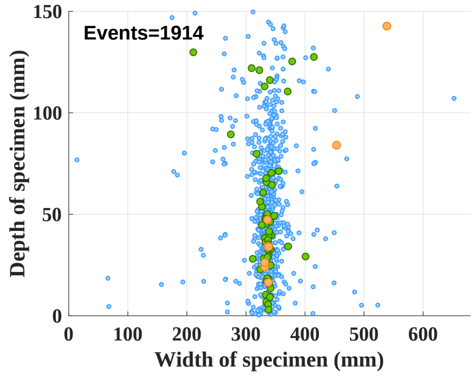
3. The effect of loading frequency is visualised through the scatter of micro cracks of smaller magnitude. We observe that density of small magnitude micro cracks increases with the increase in frequency. The more number of micro cracks generated indicates that more energy is required to break the specimen. The specimens subjected to higher frequency require more energy to fail to the specimen.

4. The magnitude of high AE energy events dissipated at failure ranges between 10^5 to 10^6 Atto Joules for specimens subjected to 2 Hz and 4 Hz whereas for specimens subjected to 0.5 Hz, the AE energy dissipated ranges between 10^4 to 10^5 Atto Joules. This trend is analogous to hysteresis energy. We observe that the magnitude of both hysteresis energy and acoustic energy increases with increase in frequency at failure

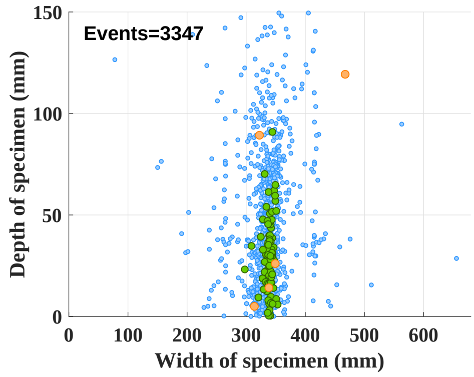
The results of acoustic emission substantiates that concrete beams subjected to lower frequencies, behave in a more brittle manner. The possible explanation for such behaviour could be that, for specimens subjected to high frequency, isolated and randomly distributed micro cracking occurs with wide scatter compared to specimens subjected to lower frequency. The randomly oriented micro cracks can blunt the effect of high stresses which in turn increases the energy required to cause failure. The visualisation of scatter of AE events along the specimen dimension could give us better clarity on the current argument. The AE events generated until failure along the dimension of concrete



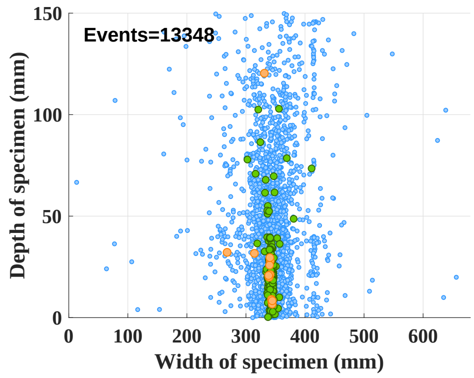
(a) Monotonic



(b) 0.5 Hz



(c) 2 Hz



(d) 4 Hz

Figure 7: Scatter of AE events on the concrete beam specimens

beam specimens subjected to different frequencies are shown in Figure 7(a)-(d). The following observations are made from these figures:

1. Figure 7(a) shows the scatter plot of AE events for specimens loaded monotonically. The high magnitude AE events are concentrated in the narrow band along the initial notch. The high and low energy AE events occurs progressively along the depth of the specimen indicating the formation of fracture process zone and propagation of macro crack.

2. For the specimens loaded under fatigue as shown in Figure 7(b)-(d), we observe that the low magnitude energy events are dominantly scattered along the depth of the specimen. The effect of frequency can be visualised in terms of width of scatter of AE events along the dimension of the specimen. We observe that the width of scatter of AE events increases with increase in frequency. For specimens subjected to higher frequency, the micro cracks are more randomly distributed with wider scatter and for the specimens subjected to lower frequency the majority of micro crack scatter falls within the narrow band along the notch.

These observation further substantiate our previous argument of wider scatter of micro cracks in specimens subjected to high frequency which indirectly requires high energy for failure.

5 CONCLUSIONS

The effect of frequency showing counter intuitive trend of increase in fatigue life with increase in loading frequency is studied experimentally with the aid of acoustic emission sensing. The following conclusions are made from this work

1. The mechanical test results show that specimens tend to become more brittle when subjected to lower frequency as they fail at higher stiffness and with lower hysteresis energy dissipation compared to the specimens subjected to higher frequencies.

2. The acoustic emission results has revealed that the width of micro crack scatter along the specimen length is greater for specimens subject to higher frequency compared to those subjected to lower frequencies.

3. The increased fatigue life for specimens subjected to higher frequencies is attributed to widely distributed and randomly oriented micro cracks that can blunt the effect of high stresses which in turn increases the energy required to fail the specimen.

The main out come of this research work is the correlation of specimen brittleness with the applied frequency. In all the previous research work, increase in fatigue life due to applied frequency is correlated with dynamic strength of the material. The present experimental investigations show a new dimension to assess the effect of loading frequencies in terms of induced brittleness in the material.

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