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A parallel between earthquake sequences and acoustic emissions released during fracture process in reinforced concrete structures under flexural loading

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HIGHLIGHTS

- Influences of different factors on relaxation ratio of acoustic emission signals related to reinforced concrete were presented.
- Relaxation ratio analysis of AE released during reinforced concrete was discussed in detailed.
- AE based *b*-value analysis was studied for different reinforced concrete beams.

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ABSTRACT

This article reports on the influence of (i) concrete compressive strength (ii) specimen geometry (iii) change in rate of loading (iv) percentage of steel reinforcement [area of steel reinforcement as a percentage of the effective area of reinforced concrete (RC) structural member's cross section] (v) mode of failure on the relaxation ratio parameter (Colombo et al., 2005a, 2005b) of acoustic emissions (AE) released during fracture process in reinforced concrete (RC) flanged beam specimens. The aim is to study the feasibility of relaxation ratio analysis of AE signals for damage assessment in RC beams. The beam specimens were tested in the laboratory under incremental cyclic loading. The loading cycle first entered into the relaxation dominant phase in the relaxation ratio plot was equal or close to the loading cycle entering first into the heavy damage zone in the NDIS-2421 damage assessment plot proposed by Japanese society for nondestructive inspection. Further, the lowest AE based *b*-value was observed at the same or nearer loading cycle. Relaxation ratio analysis of AE signals is a useful method to assess the current load carrying capacity of a structure and state of damage in concrete structures *in-situ.*

1. Introduction

Nondestructive testing and evaluation (NDT&E) of reinforced concrete (RC) structures *in-situ* has been an important issue globally. Maintenance of RC structures is vital to ensure its intended purpose for long term. The vulnerability of these RC structures to aggressive environment, heavy traffic loads, fatigue during their service life is a serious problem. Further, damage assessment after accidents such as earthquake, impact and fire are causes of major concern for structural engineers. Also, deterioration of RC structures takes place due to aging. Identification of causes of deterioration and consequent repair/rehabilitation approach at an optimum cost needs a systematic nondestructive testing and evaluation [1].

Damage may be equal to any changes (localized or distributed) taking place inside the RC structure which leads to the degradation of the structure in-terms of loss of strength, stiffness and change in dimensions. In general, the structural damage inspection comprises of monitoring and the evaluation of the performance of each member of a concrete structure throughout its service life. Any deficiency in performance of a RC structure should be detected early for the rehabilitation of the same RC structure. The damage inspection could be a routine inspection, in-depth inspection or a special inspection. It is required to conduct investigation to know the damage state of the structures and the existence of invisible cracks [2]. Acoustic emission (AE) monitoring technique is a useful nondestructive testing method to assess the present damage condition of existing RC structures in service. The important feature of this NDT method is that it can be used for incipient failure detection through continuous and intermittent monitoring of RC structures in service [3–9].

2. Literature review

Over the past few years, researchers have attempted to study the state of the damage in RC structures using AE parameter based

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methods [10–20]. Ohtsu et al. used AE energy and Kaiser effect to study the state of damage in RC beams in a laboratory under incremental cyclic loading [21]. Researchers used AE based *b*-value to study the fracture process in RC structures and concluded that variation of AE based *b*-value showed a significant relationship with micro-cracking and macro-cracking [22–38]. Ridge and Ziehl used AE parameter cumulative signal strength to evaluate damage in concrete specimens [39]. Nair and Cai used intensity analysis of acoustic emissions to assess damage in concrete bridges *in-situ* [40]. Vidya Sagar and Raghu Prasad reviewed the literature related to parameter based AE techniques applied to concrete structures [41]. Recently, Behnia et al. reviewed application of AE monitoring techniques to study the structural health monitoring of concrete structures [42]. Several attempts have been made to study the fracture properties of concrete using AE monitoring technique [43,44] and recently Ohtsu edited research studies on AE and related NDT techniques in context of fracture mechanics of concrete, which consolidates the latest developments in application of AE monitoring technique to study fracture process in concrete [45].

3. Similarities between the earthquake sequences and AE released during fracture process in solids

During occurrence of an earthquake a sudden movement results in the release of energy stored in the earth's crust and causes vibrations that propagate outward from the source as seismic waves. Analogous to this event, a similar occurrence but on a different scale is the release of acoustic emissions during the fracture process in solids. The AE released during fracture in solids is similar to the seismic waves. Seismic waves reach the earthquake monitoring stations present on the surface of the earth. Analogously, during fracture process in solids AE sensors mounted on the surface of RC structure record the acoustic emission (micro-seismic or stress) waves. In both cases, there is a release of energy from sources located inside a medium. Therefore, release of seismic waves related to an earthquake and AE released from solids during fracture process have similarities.

An earthquake ground motion consists of three phases, viz., main shock followed by foreshocks and aftershocks. After-shocks begin in surrounding area of main shock and thus after-shocks relax the stress concentration caused by the main shock. A parallel was drawn with the earthquake sequences (or with the various phases of earthquake ground motion) and AE released during fracture process in RC beams under incremental cyclic force [46]. By using the same parallel, Colombo et al. proposed a parameter 'relaxation ratio' of AE signals shown in Eq. (1) and subsequently using the same parameter the current status of damage in RC beam specimens (with rectangular cross section) was studied in the laboratory [47,48].

$$Relaxation\,ratio\,(RR) = \frac{\text{Average energy released during unloading}}{\text{Average energy released during loading}} \quad (1)$$

$$Average\,energy\,released\,during\,loading = \frac{cumulative\,energy\,released\,during\,loading}{total\,AE\,hits\,recorded\,during\,loading} \quad (2)$$

$$Average\,energy\,released\,during\,unloading = \frac{cumulative\,energy\,released\,during\,unloading}{total\,AE\,hits\,recorded\,during\,unloading} \quad (3)$$

Average energy released during loading and loading can be calculated by using Eq. (2) and Eq. (3) respectively. Another parallel drawn between occurrence of earthquakes and AE released during fracture process in solids under force is the *b*-value analysis. Higher magnitude earthquakes occur less in number and lower magnitude earthquakes occur more in number. Similarly, during fracture process in solids the release of high amplitude AE events are in less number and low amplitude AE events are more which is known as Gutenberg-Richter (G-R) empirical relation. In context of AE monitoring technique the G-R relation is given in Eq. (4) [49,50].

$$\log_{10} N = a - b\left(\frac{A_{dB}}{20}\right) \quad (4)$$

In Eq. (4), N is the number of AE hits (or events) with an amplitude higher than A_{dB}. a is a constant determined largely by the background noise present in the surroundings of testing environment and b is the negative gradient of the curve plotted between $\log_{10}(N)$ and AE signal (in the form of sinusoidal wave) amplitude (A_{dB}) and known as AE based *b*-value [51].

4. Aim of the present study

Relatively, very less research work is reported in literature on relaxation ratio analysis of AE signals related to RC structures. There is a need to study further on practical applicability of relaxation ratio analysis of AE signals, so that the same analysis can be implemented to monitor or assess the damage condition of existing RC structures *in-situ*. Previously, researchers had implemented relaxation ratio analysis to RC structural members subjected to flexural loading. In this study, an attempt has been made to implement relaxation ratio analysis to structural members with different concrete compressive strength, percentage of steel and geometry (cross section of the test specimen). Also influence of loading rate and shear mode failure on results of relaxation ratio analysis of AE signals is studied to broaden it's applicability to RC structures *in-situ*.

Till now, these two AE parameter based analyses viz., (a) relaxation ratio (computed based on AE energy) analysis (b) AE based *b*-value (computed based on AE peak amplitudes) analysis related to RC structures have been studied separately. In this present study, an attempt has been made to link these two methods for assessing the damage state in RC structures more efficiently. By following Colombo et al. (2001, 2005a and 2005b) the aim is to assess the damage of RC structures subjected to incremental cyclic loading and to compare with the damage assessment criterion NDIS-2421 [21,52].

5. Research significance

In India, during the last 60–70 years several RC structures were constructed. It is essential to maintain these RC structures and keep in useful condition. Because deterioration is a natural phenomenon and has been seen in large number of RC structures. Therefore, a systematic approach is needed in dealing with such problems. Nondestructive testing and evaluation (scheduled or unscheduled) of in-service RC structures is required to monitor the ongoing fracture or location of a crack. The experimental study reported in this article examines the feasibility of relaxation ratio analysis of AE signals released during condition monitoring of existing RC structures without obstructing their usage.

6. Experimental program

6.1. Materials and test specimens

The details about the determination of specimen dimensions are given in [23]. A total of sixteen RC flanged beam (T-beam cross section) specimens were tested and the geometry, concrete mixture, steel reinforcement details and rate of loading applied on test specimens are given in Table 1, where A_s is area of reinforcement, that is equal to area of steel reinforcement as a percentage of the effective area of beam cross section; b_w is flanged beam rib (or web) width; D is beam overall depth. The maximum diameter of the tensile reinforcement bar used was 20 mm. Each specimen was loaded at mid-span and simply supported over a span S. Two-point loading span was 1 m with 2.6 m supporting-span (S). Total length (L) of the each test specimen was 3.2 m. The test setup is shown in Fig. 1. A schematic diagram of the reinforcement details and test specimen cross-section is shown in Fig. 2a.