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Damage limit states of reinforced concrete beams subjected to incremental cyclic loading using relaxation ratio analysis of AE parameters

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ABSTRACT

This paper presents an experimental study on damage assessment of reinforced concrete (RC) beams subjected to incremental cyclic loading. During testing acoustic emissions (AEs) were recorded. The analysis of the AE released was carried out by using parameters relaxation ratio, load ratio and calm ratio. Digital image correlation (DIC) technique and tracking with available MATLAB program were used to measure the displacement and surface strains in concrete. Earlier researchers classified the damage in RC beams using Kaiser effect, crack mouth opening displacement and proposed a standard. In general (or in practical situations), multiple cracks occur in reinforced concrete beams. In the present study damage assessment in RC beams was studied according to different limit states specified by the code of practice IS-456:2000 and AE technique. Based on the two ratios namely load ratio and calm ratio and when the deflection reached approximately 85% of the maximum allowable deflection it was observed that the RC beams were heavily damaged. The combination of AE and DIC techniques has the potential to provide the state of damage in RC structures.

1. Introduction

Maintenance of reinforced concrete (RC) structures is important to ensure long term conservation of concrete structures to serve its intended purpose. The vulnerability of these RC structures to aggressive environment during their service life is a cause of major concern for structural engineers. In general, the structural damage inspection comprises the monitoring and the evaluation of the performance of each component of concrete structure throughout its service life. Any deficiency in performance could be detected and corrected early. The inspection could be routine inspection, in-depth inspection or special inspection. The routine inspection involves a general examination of the structure to look for obvious outward physical evidence of distress that might require repair or maintenance. An in-depth inspection requires a detailed visual examination of all superstructures and substructure elements and this kind of inspection is necessary for old RC structures [1–3]. Among the many available technologies, nowadays AE monitoring, one of the non-destructive techniques (NDTs) is used to evaluate the damage in RC structures[4–19]. In general, AE technique is a passive monitoring technique which can be appropriately used for damage assessment of RC structures [4,20–24]. Usually AE monitoring is used to obtain qualitative results by observing the trends of AE parameters recorded during the experiment and the extent of damage is then determined [4,11–15,17].

Over the past few years, researchers attempted to state the damage in RC beams using parametric based AE techniques [4–19]. By defining two ratios namely calm ratio and load ratio based on AE energy and Kaiser effect, researchers assessed the state of damage in RC beams [4,11,17]. Ohtsu et al. made a damage assessment chart on the basis of load ratio and calm ratio and related them with crack mouth opening displacement (CMOD) [11]. Colombo et al. studied AE based *b*-value which is based on Gutenberg–Richter formula to study the fracture process in concrete beams and concluded that the variation of *b*-value during fracture process in RC beams showed a significant relationship with micro and macro cracking [12]. Researchers used AE energy parameter to evaluate damage of concrete beams [13–15]. By defining a parameter "relaxation ratio" Colombo et al. concluded that there is a significant change in relaxation ratio at 45% of the ultimate failure load [13,14]. Ridge and Ziehl used cumulative AE signal strength parameter to evaluate damage in concrete specimens [15]. Nair and Cai used intensity analysis technique to assess damage in concrete bridges [16]. Nowadays most of the researchers are using parametric based AE techniques because of the availability of high speed multi channel AE recording and source location systems. In the present study the limit state of serviceability conditions are used [25–34,37–39].

Research in application of AE technique to RC structures has progressed quite sufficiently. Most of the RC structures built a few decades ago are sufficiently exposed to aggressive environment and

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therefore both steel and concrete could have undergone damage. It is needed to conduct investigation regarding the state of the structures like existence of invisible cracks, and level of corrosion in steel. It is possible to know the existence of cracks by AE technique. AE technique is a non-invasive one and thus very conversant for structures under use. AE technique can easily quantify the extent of damage [4,11–15,17,20–24].

2. Research importance

By following Ohtsu et al. (2002) and Colombo et al. (2005) the aim of the present experimental study is to assess the damage of RC beams subjected to incremental cyclic loading and the present study is an extension of earlier work by the authors [11–14,40]. Earlier researchers proposed a standard (NDIS-2421: The Japanese Society for Non-Destructive Inspection (JSNDI)) to classify the damage in RC beams [11]. In general, multiple cracks take place in RC beams under bending as shown in Fig. 1, therefore utilization of CMOD of a single crack may not be appropriate. In the present study the damage in RC beams is classified on the basis of AE released, deflection, strain in steel and concrete, specified by the code of practice IS-456:2000 for different limit states[25]. According to Indian code of practice IS:456-2000, The limit state of serviceability corresponds to development of excessive deformation and is used for checking structural members in which magnitude of deformation may limit the use of the structure or its components. This limit may correspond to (a) deflection (b) cracking and (c) vibration. In general a reinforced concrete structure should satisfy the serviceability limit state, that is, if a section is of sufficient strength to support the design loads, there should not be excessive deformation and cracks which may affect the appearance. The strain in concrete is measured using DIC technique and strain in steel at mid section of the test specimen is recorded using electrical strain gauge which was embedded before casting of the RC beam specimens. The validity of the present experimental study results were compared with the assessment criterion suggested by the JSNDI [11,18–19].

3. Methods adopted to assess damage in beams

3.1. Relaxation ratio

Researchers in the past used relaxation ratio as a parameter to assess damage qualitatively in concrete beams [13,14]. The RC beams are loaded cyclically and each load cycle consists of loading and unloading phase. Earlier researchers

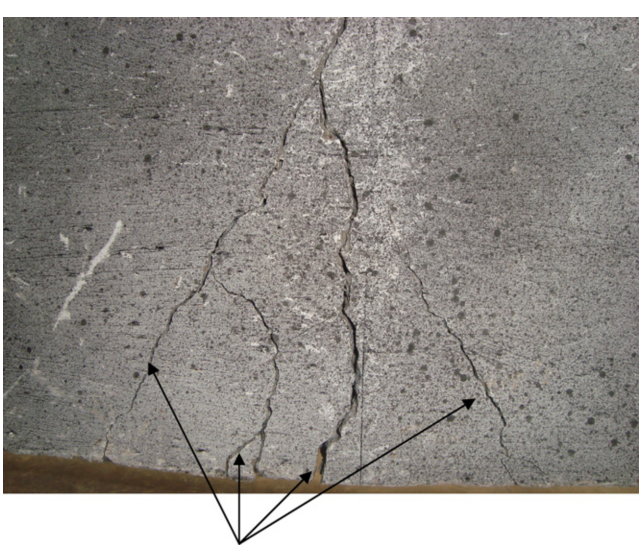

Fig. 1. Multiple cracks developed in RC beam under bending failure [40].

observed that AE activity during the unloading is generally an indication of structural deterioration. An analogous representation was drawn with earthquake sequences present in seismology and with AE released during fracture process in RC beams [13,14,26,27]. It is known that earthquake ground motion consists of three phases, viz., main shock followed by after shocks[13,14,26,27]. After shocks follow main shock. After shocks typically begin immediately after the main shock. Foreshock are smaller earthquakes that preceded the main shock. These foreshock generally occur in the vicinity of main-shock hypocenter and also part of the nucleation process. In fact, after-shocks relax the stress concentration caused by the main shock [13,14,26,27]. By using the principles of the seismology, the fracture process in a concrete test specimen at the end of a load cycle, can be considered analogously as the AE generated respectively during the loading and unloading phases [14]. In the present study authors used a parameter relaxation ratio defined by Colombo et al. [13,14]

$$\text{Relaxation ratio} = \frac{\text{Average energy during unloading phase}}{\text{Average energy during loading phase}} \tag{1}$$

$$\text{Average energy} = \frac{\text{Cumulative energy recorded for each phase}}{\text{Total number of recorded hits}} \tag{2}$$

The average energy is the cumulative energy recorded by all the sensors divided by number of recorded hits for each phase. A relaxation ratio greater than one implies that the average energy recorded during the unloading cycle is higher than the average energy recorded during the corresponding loading cycle and therefore the relaxation is dominant [13,14].

3.2. NDIS-2421. specifications for damage assessment

Under the proposed standard NDIS-2421 by the JSNDI, the Kaiser effect was evaluated as part of the criterion for damage assessment of concrete structures [4,11,17–19]. The damage assessment criterion proposed by NDIS-2421 is based on two parameters namely load ratio and calm ratio [11]. They are

$$\text{Load ratio} = \frac{\text{Load at the onset of AE activity in the subsequent loading}}{\text{The previous maximum load}} \tag{3}$$

$$\text{Calm ratio} = \frac{\text{The number of cumulative AE activities during unloading process}}{\text{Total AE activity during the last loading cycle up to maximum}} \tag{4}$$

The load at onset of AE activity and previous load in the subsequent loading were selected based on the plot between cumulative AE hits and load. The number of cumulative AE activities (viz., AE hits) and total AE activity (viz., total AE hits) during the last loading can be obtained by the AE recording system. However, in the present experimental study, the serviceability limits namely deflections, strains in steel and concrete were used to assess damage in RC beams.

4. DIC technique to measure the strain in concrete

DIC technique for measuring strain in concrete has been extensively described in the literature [28–31]. But for the sake of completeness a brief review of the relevant material will be given here. DIC technique is a field image analysis method, based on gray value of the digital images and this DIC analysis is useful to determine displacements and strains developed in a structure under load [28–32]. Earlier researchers used DIC technique for measurement of strain in concrete from the digital images recorded during experiments [28,30]. DIC is based on the maximization of a correlation coefficient that is determined by examining pixel intensity array subsets on two or more corresponding images and extracting the deformation mapping function that relates the images recorded during the experiments. An iterative approach is used to minimize the 2D correlation coefficient by using nonlinear optimization techniques [29,31,32]. The cross correlation coefficient r_{ij} is defined as

$$r_{ij}\left(u, v, \frac{\partial u}{\partial x}, \frac{\partial u}{\partial y}, \frac{\partial v}{\partial x}, \frac{\partial v}{\partial y}\right) = -\frac{\Sigma i \Sigma j [F(x_i, y_i) - \overline{F}][G(x_i^*, y_i^*) - \overline{G}]}{\sqrt{\Sigma i \Sigma j [F(x_i, y_j) - \overline{F}]^2 \Sigma i \Sigma j [G(x_i^* y_i^*) - \overline{G}]^2}} \tag{5}$$

$F(x_i, y_j)$ is the pixel intensity or the gray scale value at a point (x_i, y_j) in the undeformed image, $G(x_i^*, y_j^*)$ is gray scale value at a point