**INTRODUCTION**

Most of the concrete structures show the signs of distress because of the ageing of concrete and environmental effects. In general, non-destructive testing (NDT) is required to assess damage in concrete structures [1-2]. AE technique is a well-established NDT method and it is one of the most sensitive techniques to monitor non-invasively the deformation, fatigue and fracture of materials including concrete and the use of AE technique has been described in the literature extensively [1-2]. In fact microcracking is the main source of AE activity and by analyzing the measurable AE activity the state of damage can be determined. 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. In the present study the load is applied in incremental cycles on RC beams. By defining two ratios namely calm ratio and load ratio based on AE energy and Kaiser effect, researchers studied state of damage in RC beams under cyclic loading [3-6]. Damage assessment chart prepared on the basis of two ratios were compared with CMOD [3,14]. Colombo et al. used Gutenberg -Richter formula to calculate AE based b-value to study the fracture process in concrete beams and concluded that the variation of b-value showed a significant relationship with microcracking and macrocracking [4]. Researchers used AE energy parameter to evaluate damage of concrete beams. 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. In the past researchers attempted to use cumulative signal strength parameter to evaluate damage in concrete specimens [2,7]. Nowadays most of the researchers are using parametric based AE techniques because of the high recording and data storing speeds [2].

Earlier researchers proposed a standard (NDIS-2421: The Japanese Society for Non-Destructive Inspection (JSNDI)) to classify the damage in bridge beams [8-9]. In general, multiple cracks takes place in reinforced concrete beams under bending, therefore utilization of CMOD of a single crack may not be appropriate [14]. By following Ohtsu et al. and Colombo et al. in the present study the damage in RC beams is classified on the basis of AE released, deflection, strain in steel and concrete, specification given by the code of practice IS-456:2000 for different limit states [11]. 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. The validity of the present experimental study results were compared with the assessment criterion suggested by the JSNDI [7].

**METHODS ADOPTED TO ASSESS DAMAGE IN BEAMS**

**Relaxation ratio**

An analogous representation was drawn with earthquake sequences, present in seismology and with AE released during
fracture process in RC beams [5-6]. Earthquake ground motion consists of three phases, viz., main shock followed by foreshocks and after shocks. After-shocks begin in surrounding area of main shock and thus after-shocks relax the stress concentration caused by the main shock. 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 as the AE generated respectively during the loading and unloading phases. In the present study authors used a parameter relaxation ratio defined by Colombo et al [5-6].

\[
\text{Relaxation ratio} = \frac{\text{Average energy during unloading phase}}{\text{Average energy during loading phase}} \quad (1)
\]

The average energy was the cumulative energy recorded by all the sensors divided by total 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 [5].

**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. The damage assessment criterion proposed by NDIS-2421 and is based on two parameters namely load ratio and calm ratio [8-9].

\[
\text{Load ratio} = \frac{\text{Load at the onset of AE activity in the subsequent loading}}{\text{The previous maximum load}} \quad (2)
\]

\[
\text{Calm ratio} = \frac{\text{The number of cumulative AE activities during unloading process}}{\text{Total AE activity during the last loading cycle up to maximum}} \quad (3)
\]

Based on Kaiser effect the load ratio was defined. 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.

**EXPERIMENTAL PROGRAM**

A total of 9 RC beams (28-day compressive strength is 58 MPa) were tested and the geometric details of these specimens are given in Table 1. The maximum size of coarse aggregate was 20mm. An electrical strain gauge was affixed to the main reinforcing bar before casting to measure the strain in steel at mid-section of the specimen and during the test DIC technique was performed to measure the surface strain in concrete. The experimental setup consisted of a servo hydraulic loading frame with a data acquisition system and the AE monitoring system [Fig.1]. A steel I-beam was placed beneath the actuator to transfer the load as two point loads. The load was applied in incremental cycles till failure of the specimen. The total number of cycles varied for different specimens.

The data acquisition records load, displacement at centre and 1/3 span from the ends of the beam, strain in the steel and time. Displacement of the beam was measured at three locations using a LVDT, placed on the underside of the specimen. The locations of each LVDT were 1 meter from the right and left end of the specimen and at midspan of the specimen. DIC technique has been used to measure the 2D surface displacements and strain in concrete along with the available mathematical program MATLAB [15]. The images have been taken for all the cycles using a digital camera and a remote control to avoid any vibration and also to keep the distance between camera lens and the specimen unchanged.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>size</th>
<th>Ø (mm)</th>
<th>n</th>
<th>A (mm²)</th>
<th>L(mm)</th>
<th>S(mm)</th>
<th>b(mm)</th>
<th>D(mm)</th>
<th>p (%)</th>
<th>a/d</th>
<th>P u (kN)</th>
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<tbody>
<tr>
<td>LL1</td>
<td>Large</td>
<td>20</td>
<td>3</td>
<td>943</td>
<td>3200</td>
<td>3000</td>
<td>150</td>
<td>450</td>
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<td>2.0</td>
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<tr>
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<td>3</td>
<td>943</td>
<td>3200</td>
<td>3000</td>
<td>150</td>
<td>450</td>
<td>1.396</td>
<td>2.0</td>
<td>330.0</td>
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<tr>
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<td>3</td>
<td>943</td>
<td>3200</td>
<td>3000</td>
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<td>2</td>
<td>628</td>
<td>3200</td>
<td>3000</td>
<td>150</td>
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<td>1.395</td>
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<tr>
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<td>2</td>
<td>628</td>
<td>3200</td>
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<tr>
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<td>1.506</td>
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<tr>
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<td>3</td>
<td>339</td>
<td>3200</td>
<td>3000</td>
<td>150</td>
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</table>

Ø=nominal diameter of reinforcement; n=number of reinforcement bars; A= area of reinforcement; L=beam length; S=Span of the beam; b=beam width; D= Beam depth; p= %of reinforcement; a/d=ratio of shear span to depth; P u = final failure load;
The AE monitoring system had 8 channels one for each of the 8 resonant type sensors (resonant type R6D). The AE sensor had peak sensitivity at -75 dB with reference 1V/mbars. The operating frequency of the sensor was 35 kHz – 100 kHz.

The AE signals were amplified with a gain of 40 dB in a preamplifier [10,12].

RESULTS AND DISCUSSION

It is observed that number of cycles or rate of loading has influenced the AE activity recorded. Most interestingly, a new observation here is that AE energy also varies with beam depth and it increases with increase in beam depth. The concrete used was 58 MPa. Such a concrete would be relatively less heterogeneous. The reason is that in such high grade concrete the cement matrix is much stronger and the bond between aggregate and cement mortar is also very strong. During the fracture process AE event with high energy content will release. The same trend is noted in specimens with depth 300 mm and 150 mm. Therefore may be loading rate influences the AE activity proportionately. Figure 3 shows typical recorded plots of load versus time, load versus deflection and load versus axial strain in steel at mid section of the specimen with depth 450mm respectively. It is interesting to see that the strain in steel yielded at 0.002 of the maximum load[13].

Figure 3 shows the relaxation ratio plots for most active channel 3 for specimens with depth 450 mm, 300 mm. Relaxation ratio versus loading cycle number plots is divided into two phases with a dotted horizontal line at relaxation ratio equals to one. The trend was changed when the load reaches near to the 75.75% (450mm depth specimen) and 84.2% (300 mm depth specimen) of maximum failure load. From these

![Image](image-url)
In serviceability limit state a structure remain functional for its intended use subject to routine loading, and as such the structure must not cause users discomfort under routine conditions. In fact a concrete structure is deemed to satisfy the serviceability limit state when the constituent structural elements do not deflect by more than the limits laid down in the codes of practice IS:456:2000 [11]. In the present study authors assumed that the damage in concrete is considered to be serviceable state when the deflection limit is in the range of (0-50)%. No cracks were noticed on the specimen in the serviceable state and the concrete is considered to be safe. When the deflection value is in the range of (50-85)% of the maximum allowable the damage is considered to be non-serviceable state. Micro cracks were observed on the surface of the specimen in this state of damage. The third state of damage is collapse when the deflection value is greater than 85% of the maximum allowable. The specimen is considered to be in a state of collapse when the micro cracks coalesce to form macro cracks on the surface of the specimen and the beam is considered to be collapsed. It is also noted that till the loading cycle number 10 the damage is in the serviceable state and from load cycle 10 to load cycle 15 it is in non-serviceable state and last two cycle’s near-collapse in specimens with depth 450 mm. In case of specimens with depth 300 mm the first 5 cycles are in serviceable state and next three are in non-serviceable state.

Concrete structures contain flaws such as pores, air voids, and shrinkage cracks even before they are loaded. The flaws, especially the small cracks, grow stably under external loading. The small cracks join together with existing or newly-formed micro cracks to form macro crack which cause the collapse of the structure [14]. When the cracks are developing there is a dominance of primary AE activity and once the damage have progressed further the secondary AE activity is prevailed in the relaxation phase. It is interesting to see that relaxation plot constructed from the recorded AE energy follow a similar trend that was obtained by Colombo et al. [5]. It is observed that there is a change in trend near loading cycle 2 and 3.

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serviceable state and last 2 are near collapse. However in specimens of depth 150mm 4 load cycles were applied and the specimen shows a trend as observed by earlier researchers [3,5-6]. The displacement obtained from DIC and displacement recorded by LVDT follows approximately the same trend. Finally, the x-direction strain in concrete versus image number has been plotted corresponding to the load to see the variation of strain in concrete in a cyclic loading. It was observed that after 8th cycle the strain in concrete becomes positive. The variation of strain in concrete measured using DIC technique increases with the increase in loading. The analysis described in using load ratio and calm ratio is compared with NDIS-2421 quantitative assessment criterion proposed by the committee JSNDI. The limits of the classification are fixed on the basis of the maximum deflection recommended by code of practice IS: 456-2000. The data recorded from the most active channel number 3 is used for the calculations of load ratio and calm ratio. The results are shown in Figure 4 for specimens with depth 450 mm. From Figure 4 it can be seen that specimens with depth 450 mm, the limits for load ratio and calm ratio are 0.9. The assessment chart for all specimens (LM1, LM2 and LM3) with depth 300 mm is superimposed and the limits for load ratio and calm ratio are 1.1 and 0.8. In case of specimens with depth 150 mm the limits for load ratio is 0.6 and for calm ratio is 0.6. The minor damage has been taken place in the range of 0% to 50% of the mid span deflection and intermediate damage falls in the range of 50% to 85% and the heavy damage occurs above 85% of the mid span deflection. A similar assessment criterion is prepared for LL1 specimen on the basis of strain in steel and strain in concrete shown in Figure 4.

CONCLUDING REMARKS

Based on the above experimental results the following three major conclusions can be drawn

1. Coupling AE technique and DIC technique is useful to assess damage concrete structures remotely without hindering the usage.

2. The damage levels estimated from the maximum deflection were in agreement with the damage qualified by load ratio and calm ratio.

3. During the fracture process of RC beams, the damage levels qualified by AE technique shifts from minor to major levels as the strain in steel and concrete increases.

Further work is needed to establish the applicability of this method to assess damage in RC beams.

REFERENCES


8. RILEM TC 212-ACD. Mat and Str,43 , pp.1187-1189 (2010).


