Fracture Formation Evaluation of Reinforced Concrete Beam Subjected to Cycle Loading Using Acoustic Emission Technique

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Abstract. Acoustic emission (AE) technique is one of the non-destructive evaluation (NDE) techniques that have been considered as the prime candidate for structural health and damage monitoring in loaded structures. In present study, AE technique with a new approach was employed to investigate the process of fracture formation in reinforced concrete (RC) structure. Thirty RC beam specimens with continuous and non-continuous longitudinal rebar were prepared. The RC beams were tested under loading cycle and were simultaneously monitored using AE. The AE test data was analyzed using Relaxation, Load and Calm ratio. The trend of these methods during loading and unloading was compared with behaviour of each type of specimens. The trend of Relaxation ratio and Calm and Load ratio method during loading and unloading showed that these methods are strongly sensitive with cracks growth in RC beam specimens and were able to indicate the levels of damage. Also, results showed that AE can be considered as a viable method to predict the remaining service life of reinforced concrete. In addition, with respects to the results obtained from Relaxation, Load and Calm ratio indicated, a new chart is proposed.

Key words: Reinforced concrete beam; Acoustic emission; Relaxation ratio; Calm and Load ratio; nondestructive evaluation technique

1. INTRODUCTION

Acoustic emission (AE) technique is one of the non-destructive evaluation (NDE) techniques that have been considered as the prime candidate for structural health and damage monitoring in loaded structures (Surgeon and Wevers, 1999). The main goal of the monitoring of AE phenomena is to provide a series of useful information by the correlation of AE signals with growing fracture process (Romaniv et al., 1987).

AE technique is used to evaluate of concrete structures damage intensity in real time. The primary sources of acoustic emission in concrete structures are numerous and include cracking of the concrete, rubbing of crack surfaces during crack closure, debonding of the reinforcing steel from the surrounding concrete (Pollock, 1981).

AE data can be evaluated by means of several methods. Relaxation ratio and Calm and load ratio which are derived from events during unloading and loading are reasonable methods for evaluation structure under cyclic load. A few works were found that Relaxation ratio has been used for evaluation of concrete structure such as Colombo et al. (2005), Liu and Ziehl (2009) and Proverbio (2011). In addition, several works was found that Calm and Load ratio has been used for evaluation of concrete structure such as Ohtsu et al. (2002), Luo et al. (2004), Colombo et al. (2005), Lovejoy (2008), Liu and Ziehl (2009), Proverbio (2011) and Vidya Sagar et al. (2012).

In main objective of this current study was to evaluate damage assessment of RC beam using Relaxation and Calm and Load ratio. Commonly, previous works has been evaluated for RC beams in flexural mode. In this research RC beam in two modes failure (flexural and shear) and failure due to slippage of reinforcement in concrete were considered. Also, a new chart for evaluation of the RC beam using Relaxation and Calm and Load ratio was suggested. The ultimate goal of this current study is the possibility in implementing for a remote monitoring procedure of concrete structures using AE.

2. FUNDAMENTAL THEORETICAL

2.1. Relaxation Ratio

Commonly, the load pattern of AE test is load cycles which consist of two phase: a loading and an unloading phase. AE activity during unloading is an indication of structural instability (Ohtsu et al., 2002). In respect to the AE activity during loading and unloading, quantification of Relaxation Ratio was proposed by Colombo et al. (2005). In previous
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Experiments, the AE energy has been used to describe Relaxation ratio. In these study the AE signal strength was used which shown the most effective parameter in damage evaluation. The relaxation ratio is expressed in terms of signals strength and defined as:

\[
\text{Relaxation ratio} = \frac{\text{Average signal strength during the unloading}}{\text{Average signal strength during the loading}}
\]

2.2. Calm and Load ratio

One of the important damage assessment methods is based on two parameters: calm and load ratio. Three levels of concrete damage (heavy, moderate and low) using cross plotting these two ratios can be identified. Calm ratio is based on relation AE activity during loading and unloading (Colombo et al., 2005). The Load ratio is based on the concept of Kaiser Effect and is defined as the ratio between the load at the onset of AE activity under repeated loading and previous load (Proverbio, 2011). However, according to Gross and Ohtsu (2008), calm and load ratio was defined as:

\[
\text{Load ratio} = \frac{\text{Load at onset of active during unloading}}{\text{Maximum load during pervious loading}}
\]

\[
\text{Calm ratio} = \frac{\text{The number of cumulative AE activity during}}{\text{The total AE activity during pervious loading}}
\]

3. METHODOLOGY

3.1. Material details

The specimens used in this study were reinforced concrete (RC) beam. The dimensions of the RC beams were 1500 mm in length with a 250x250 mm cross section. RC beam specimens were reinforced with four 10 or 12 mm diameter deformed steel bars and with stirrups of 6mm diameter at 200 mm center to center spacing. A total of thirty reinforced concrete beams specimens in ten types were cast. Figure 1 shows the dimension of all types of the RC beam specimens. The water to cement ratio was 0.5 and the material proportions were 1:2:2.5:0.5 by weight of cement, sand, aggregate and water respectively. The average compressive strength of concrete at 28 days was 25Mpa.

![Fig. 1: Dimension of all types of the RC beam specimens](image)

(a) (b)
3.2. Cyclic loading test monitoring using AE technique

A total of thirty RC beam specimens described earlier were tested under loading cycle. In order to perform acoustic emission monitoring, an eight channel AE system (DISP-8PCI) manufactured by Physical Acoustics Corporation (PAC) was employed. Four R6I sensors with the resonance frequency of approximately 60 kHz were used. The AE systems hardware was set up for threshold level of 45dB for all channels in order to avoid the possibility of noise effect. The load was applied at the mid span of the RC beam specimens. The load was applied in 10kN steps at mid span of RC beam. The load was going up from 0.5kN to maximum of each loading cycle and held constant for one minute. Then, the load was removed down from maximum of each loading cycle to 0.5kN and was held for 2 minutes. The test was monitored by AE throughout the test. The measurement including load, mid span deflection and AE data were recorded continuously during the three point bending test.

4. RESULTS AND DISCUSSIONS

4.1. Overall responses of test RC beam to cyclic loading

The RC beams were tested in three point bending test according to described previously. A summary of three-point bending results as shown in Table 1. In addition, Figure 2 shows the behavior of RC beam specimens under loading cycle. The behavior RC beam specimens under load can be divided into six stages of failure namely: (I) Micro-cracking (II) Initial flexural cracks visible, (III) Distributed flexural cracks, (IV) Mixed flexural and shear cracks, (V) Localized crack propagation and (V) Failure. With respect to the behavior of the RC beam specimens under loading cycle, specimens can be divided in three types: A, B and C. The specimens of type A include RCBLC1, RCBLC2, RCBLC6 and RCBLC7 which the longitudinal overlap length was not enough and were failed due to slippage of reinforcement in concrete. The load failure for all type A specimens were between 60kN to 70kN and location was at the connection zone. The specimens of type B include RCBLC3, RCBLC4 and RCBLC5 that were failed in flexural mode. The specimens of type C include RCBLC8, RCBLC9 and RCBLC10 that were failed in shear mode. In addition, the load failure for all specimens of type B and C were between 90kN to 100kN and location was outside of the connection zone.

<table>
<thead>
<tr>
<th>Type</th>
<th>Specimen</th>
<th>L- bar size (mm)</th>
<th>Overlap length (mm)</th>
<th>Failure load (kN)</th>
<th>Failure mode</th>
<th>Failure zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>RCBLC1</td>
<td>100</td>
<td>150</td>
<td>52</td>
<td>Flexural</td>
<td>Connection</td>
</tr>
<tr>
<td>A</td>
<td>RCBLC2</td>
<td>100</td>
<td>250</td>
<td>65</td>
<td>Flexural</td>
<td>Connection</td>
</tr>
<tr>
<td>B</td>
<td>RCBLC3</td>
<td>100</td>
<td>350</td>
<td>90</td>
<td>Flexural</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>RCBLC4</td>
<td>100</td>
<td>450</td>
<td>94</td>
<td>Flexural</td>
<td>-</td>
</tr>
<tr>
<td>B</td>
<td>RCBLC5</td>
<td>100</td>
<td>-</td>
<td>90</td>
<td>Flexural</td>
<td>-</td>
</tr>
<tr>
<td>A</td>
<td>RCBLC6</td>
<td>120</td>
<td>150</td>
<td>53</td>
<td>Flexural</td>
<td>Connection</td>
</tr>
<tr>
<td>A</td>
<td>RCBLC7</td>
<td>120</td>
<td>250</td>
<td>67</td>
<td>Flexural</td>
<td>Connection</td>
</tr>
<tr>
<td>C</td>
<td>RCBLC8</td>
<td>120</td>
<td>350</td>
<td>90</td>
<td>Shear</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>RCBLC9</td>
<td>120</td>
<td>450</td>
<td>100</td>
<td>Shear</td>
<td>-</td>
</tr>
<tr>
<td>C</td>
<td>RCBLC10</td>
<td>120</td>
<td>-</td>
<td>98</td>
<td>Shear</td>
<td>-</td>
</tr>
</tbody>
</table>

4.2. Relaxation ratio analysis

The AE data obtained in test were analysed in order to carry out a relaxation ratio analysis. The Relaxation ratios in term of signal strength during loading and unloading phase for all channels were calculated. Figure 3 shows the trend of Relaxation ratio for all RC beam specimens.
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Fig. 2: The behaviour RC beam specimens under loading cycle

Fig. 3: Relaxation ratio for all RC beam specimens
Figure 3(a) (b) (c) (d) shows the trend of Relaxation ratio for all RC beam specimens of Type A. Data points show that during cycle 1 to 3 (10kN to 30kN) Relaxation ratios is less than one. Also, from loading cycle 4 (40kN) when the flexural cracks were observed until specimen failure, Relaxation ratio is greater than one. Figure 3 (e) (f) (g) shows the trend of Relaxation ratio for all RC beam specimens of Type B. Data points show that during cycle 1 to 4 (10kN to 40kN) relaxation ratios is less than one. Also, from loading cycle 5 (50kN) until specimen failed in flexural mode, Relaxation ratio is greater than one. Figure 3(h) (i) (j) shows the trend of Relaxation ratio for all RC beam specimens of Type C. Data points show that during cycle 1 to 5 (10kN to 50kN) Relaxation ratios is less than one. Also, from loading cycle 6 (60kN) until specimen failed in flexural mode, Relaxation ratio is greater than one.

Relaxation ratio is based on comparison of AE activity during loading and unloading phase. Relaxation ratio less than one shows that AE events in loading phase are dominant. Also the relaxation ratio greater than one shows that AE events in unloading phase are dominant. The results of this research show that for specimens of Type A which had a overlap length of 150mm or 250mm and were failed at connection zone due to slippage of the reinforcement in concrete, an inversion of trend in Relaxation ratio occurs when load is approaching to 40kN. Also, for all specimens of Type B that were failed in flexural mode, an inversion of trend in load ratio occurs when load is approaching to 50kN. In addition, for Type C that was failure in shear mode, an inversion of trend in load ratio occurs when load was approaching to 60kN.

Commonly, fracture mode of cracking with the progress of fracture in concrete structure is changing from the tensile type of fracture to the shear type of fracture. Crack opening is a principal motion when tensile fracture cracks are nucleated, while sliding on an existing crack is a major motion to generate the shear fracture cracks (McCabe et al., 1976). In early stages, tensile fracture cracks are primary source of AE activities. As approaching to the final failure, the shear fracture cracks are primary source of AE activities. AE activity as the shear fracture cracks could be generated during unloading (Grosse and Ohtsu, 2008).

In addition, in loading phase the cracks are the predominant source of AE activity whiles in the unloading phase the friction are sources prevail of AE activity (Colombo et al., 2005b). Therefore, it could be said that in the early stages, I and II, the tensile cracks are the primary source of AE activity. Thus, AE activity during loading phase is dominant. As approaching the final failure, shear cracks and friction between cracks are the primary source of AE activity. Thus, AE activity during un-loading phase is dominant.

Therefore, for specimens of types of B and C, it could be said that in the early stages stage (I and II), the tensile cracks are primary source of AE activity. Thus, AE activity during loading phase is dominant. Also, as approaching to the final failure, shear cracks and friction between cracks are the primary source of the AE activity. Thus, AE activity during un-loading phase is dominant.

In addition for types of A samples, at the early stage of loading, the tensile cracks are primary source of AE activity. Thus, AE activity during loading phase is dominant. Also, in this stage the behaviour of specimens is similar to specimens of type B and C. As approaching the final failure, the behaviour of specimens of type A is not similar to type B and C. In this stage, the specimens of type A of specimens due to slippage of reinforcement in concrete were failed and the slippage of reinforcement in concrete is the primary source of AE activity.

However, the results show that in the stage of micro cracks and initial crack propagation, Relaxation ratio is less than one. Also, in stage of the cracks distribution until specimen failure relaxation ratio is more than one. In addition, the results show that when load is greater than 45%, 55% and 65% of the ultimate bending load for type A, B and C respectively, Relaxation ratio is more than one.

A few works could be found in which AE activity was considered using relaxation ratio. Such as Colombo et al. (2005) and Liu and Ziehl (2009). Colombo et al. (2005) investigated the number of RC beam under cyclic load using Relaxation ratio analysis. They found that Relaxation ratio is more than one when load is greater than approximately 45% of the ultimate bending load. Also, Liu and Ziehl (2009) found that Relaxation ratio increased with load to yield load and this measure was relatively stable and was not well-suited to post-yield load evaluation because the ratio often decreased significantly after yield load. Also, no clear trend was observed for the shear specimens.

4.3. Calm ratio

The AE data were processed in order to carry out a Calm ratio analysis. The Calm ratios in terms of signal strength during loading and unloading phase for all channels were calculated. Figure 4 shows the trend of Calm ratio for all RC beam specimens.
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Fig. 4: Calm ratio for all RC beam specimens

Figure 4 (a) (b) (c) (d) shows the trend of Calm ratio for all RC beam specimens of type A. Data points show that during cycle 1 to 3 (10kN to 30kN) when the behaviour of RC beam specimens is in stage of micro-cracking, Calm ratio is low level and less than 0.05. Also, from loading cycle 4 (40kN) when the flexural cracks were observed, Calm ratio is increased to 0.25. Figure 4 (e) (f) (g) (h) (i) (j) shows the trend of Calm ratio for all RC beam specimens of type B. Data points show that during loading cycle 1 to 2 when the behaviour of RC beam specimens was in stage of micro-cracking and during loading cycle 3 to 4 in stage of observation of first cracks, Calm ratio is low level and less than 0.05. Also, from loading cycle 5 (40kN) when flexural cracks were distributed, Calm ratio is increased to 0.25.

Several works were found that Calm ratio has been used for evaluation of RC structure such as Ohtsu et al. (2002), Luo et al. (2004), Colombo et al. (2005), Lovejoy (2008), Liu and Ziehl (2009) and Proverbio (2011). They found that for failure in flexural mode, Calm ratio was relatively stable and increased with load sets up to yield. It was not well-suited to post-yield evaluation because the ratio often decreased significantly after yield. The results obtained in this study for failure in flexural mode are similar to previously works.

4.4. Load ratio

The Load ratio for all RC beams was calculated. Figure 5 shows the trend of Load ratio versus cycle number for each sample of each type. The results
show that load ratio decreases with increasing load. Also, the results indicated in stage of micro cracks, load ratios is more than one and then an inversion of trend in Load ratio occurs and the Load ratio is less than one. This change occurs when the cracks were observed. Load ratio is based on the concept of Kaiser Effect and a load ratio which is more than 1, is a criterion of a structure in good condition (Colombo et al. 2005). The results of Load ratio analysis shows that initial cracks associated with an inversion of trend in Load ratio from more than that one to less than one.

Several works was found that Load ratio has been used for evaluation of RC be concrete structure such as Ohtsu et al. (2002), Luo et al. (2004) , Colombo et al., (2005) , Lovejoy (2008), Liu and Ziehl (2009) and Proverbio (2011). They found that Load ratio was increased associated levels of Damage. The results obtained in this study show that Load ratio was increased associated levels of damage and initial cracks, Load ratio is less than one.

4.5. Calm and Load ratio chart

According to NDIS 2421, damage assessment could be evaluated by using two ratios: Load and Calm Ratios (Colombo et al., 2005). Calm and Load ratio chart is divided in three level of damage: low, moderate and high. Load ratio more than 1 is a criterion of a structure in good condition (Colombo et al. 2005). Thus, an appropriate limit value for Load ratio can be 1.0. In the relaxation ratio chart for RC beam, points move from a ‘loading dominant’ to a ‘relaxation dominant’ condition from loading cycle 4, 5 and 6 for specimens of type A, B and C. With respect to the results of Relaxation ratio, an appropriate limit value for Calm ratio can be identified as any justification 5%. Calm and load ratio chart was plotted with considering two limit values as shown in Figure 6.

5. CONCLUSIONS

This paper provides the results from tests on RC beam under loading cycle and was monitored by AE throughout the test. On the basis of AE activities, the analysis of signal characteristics using ratios of Relaxation, Load and Calm and with regard to damage levels, the conclusions are presented below:

1. Three levels of damage in concrete structure can be identified using this chart by cross plotting Relaxation ratio and Calm and Load ratio.
2. The relaxation ratio was dominated with approaching load to 40 to 60% of the ultimate load for three types of RC beam specimens.
3. The trend of Relaxation ratio and Calm and Load ratio method during loading and unloading showed that these methods are strongly sensitive
with cracks growth in RC beam specimen and were able to indicate the levels of damage.

4. Results showed that AE can be considered as a viable method to predict the remaining service life of reinforced concrete.

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Alireza Panjsetooni was born in Western area of Iran on 2rd January 1976. His first degree at University Tabriz in Bach of Civil Eng(Hons) 2000. Then he continued deeply in Master of earthquake Engineering (M.Struct) at Universiti Tehran in 2008 and currently his pursuing in PhD level at Universiti Sains Malaysia in Structural Health Monitoring.

Norazura Muhamad Bunnori (PhD) has been involved in Acoustic Emission (AE) technique since 2004 while she was pursuing her PhD study at Cardiff University, Wales, UK. She was graduated from Cardiff University in 2008 and continues with the AE research area in Universiti Sains Malaysia (USM), Malaysia. Currently she is working as a Senior Lecturer at School of Civil Engineering, Universiti Sains Malaysia (USM) since 2009. The research covered several topics of AE applications and analysis (quantitative and qualitative). The aim is to continue the AE study especially in Structural Health Monitoring (SHM) research area and to discover more in this potential area. The passion towards AE is deep and she believes that there are a great number of information can be studied and discovered with this tool.