Hindawi Publishing Corporation
Chinese Journal of Engineering
Volume 2013, Article ID 126509, 7 pages
http://dx.doi.org/10.1155/2013/126509

Research Article

Fracture Formation Evaluation of Reinforced Concrete Structure Using Acoustic Emission Technique

Alireza Panjsetooni,[1] Norazura Muhamad Bunnori,[1] Amir Hossein Vakili,[1] Zohreh Shirkhani,[2] and Zeinab Shirkhani[3]

[1] *School of Civil Engineering, Engineering Campus, Universiti Sains Malaysia (USM), Seri Ampangan, Seberang Perai, Malaysia*
[2] *Department of Biology, Payame Noor University, P.O. Box 19395-4697, Tehran, Iran*
[3] *Governor General Office of Ilam, Ilam, Iran*

Correspondence should be addressed to Alireza Panjsetooni; alireza5civil@yahoo.com

Received 7 July 2013; Accepted 7 August 2013

Academic Editors: R. Maceiras and G. Xie

Acoustic emission (AE) is an important nondestructive evaluation (NDE) technique used in the field of structural engineering for both case local and global monitoring. In this study AE technique with a new approach was employed to investigate the process of fracture formation in reinforced concrete structure. A number of reinforced concrete (RC) one story frames were tested under loading cycle and were simultaneously monitored using AE. The AE test data was analyzed using the relaxation ratio and calm and load ratio method. Also, the relaxation ratio was dominated with approaching load to 58% of the ultimate load. In addition three levels of damage using calm and load ratio were distinguished. 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 frame 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 respect to the results obtained from relaxation ratio and, load and calm ratio indicated, a new chart is proposed.

1. Introduction

AE testing is a useful nondestructive technique for real-time examination of the behaviour of materials deforming under stress [1]. 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 [2]. The wide range for application of acoustic emission is between seismic event as the largest scale and the movement of small numbers of dislocation in material as the small scale [3]. The primarily sources of AE are microcracking, macrocracking, compression failure, yielding, fracture, debonding between materials, sliding, and friction between interfaces [4].

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 of structure under cyclic load. The relaxation ratio and calm and load ratio have been used by several researchers to evaluate structural damage. A few works found that relaxation ratio have been used for evaluation of concrete structure such that [5–7] have been investigating several RC beams under cyclic load using relaxation ratio. They found that relaxation ratio is more than one when approximately 45% of the ultimate bending load was reached. In addition, several works found that calm and load ratio has been used for evaluation of concrete structure such as [5, 6, 8–11].

Reference [11] investigated a large number of full-scale laboratory test beams similar to highway bridge structure under a cyclic load using AE technique. They suggested a new threshold on the load and calm ratios specific to this class of structure and loading. Reference [10] evacuated global monitoring of concrete bridge using AE technique. They reported the suitability of AE to monitor large concrete structure using the values of quantification indices like the calm and load ratio.

The main objective of this current study was damage evaluation assessment of RC frame with a new approach and

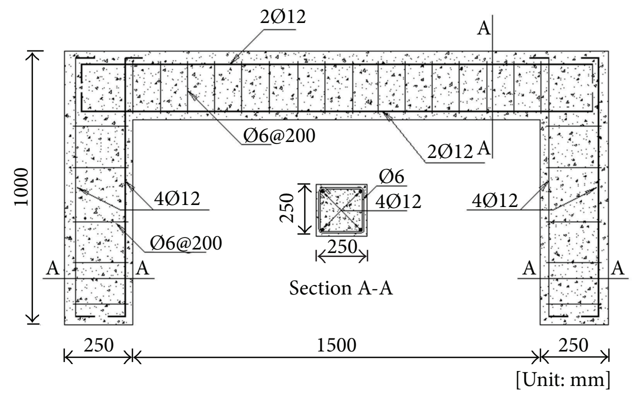

FIGURE 1: Detail and dimension of RC frame specimen.

performance using relaxation ratio and calm and load ratio method. Commonly, previous works using relaxation ratio have been focused on local evaluation of RC beams. However in this research, suitably of this method for global evaluation of RC frame was investigated. Furthermore, calm and load radio method has been used for local and global evaluation of RC beams.

2. Methodology

2.1. Relaxation Ratio. Commonly, the load pattern of AE test is to load cycles which consist of two phase: a loading and an unloading phase. AE activity during unloading is an indication of structural instability [8]. With respect to the AE activity during unloading, quantification of relaxation ratio was proposed by [5]. In previous experiments, the AE energy has been used to describe the relaxation ratio. In this study, AE signal strength was used which combines both amplitude and duration of AE and is more reasonable for evaluation of damage. The relaxation ratio is expressed in terms of signals strength and is defined as

$$\text{Relaxation ratio} = \frac{\text{Average signal strength during the unloading}}{\text{Average signal strength during the loading}}. \quad (1)$$

2.2. Calm and Load Ratio. One of the important damage assessment methods is based on correlation of calm and load ratio. This method was presented by Yuyama et al. (1999) and [8]. This method came into being a testing standard in the form of NDIS-2421 [12]. The two ratios can be identified by cross for three levels of concrete damage (heavy, moderate, and low). Calm ratio is based on relation AE activity during loading and unloading. 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 [13]. Calm and load ratio was defined as [14]

$$\text{Load ratio} = \frac{\text{Load at the onset of AE activity in the subsequent}}{\text{Maximum load during previous loading history}},$$

$$\text{Calm ratio} = \frac{\text{The number of cumulative AE activities during the unloading}}{\text{Total AE activity during the last loading cycle up to the maximum}}. \quad (2)$$

3. Experimental Procedure

3.1. Material Details. A series of experiments was conducted on reinforced concrete (RC) frame. A total of five RC frame specimens were built. Figure 1 shows the detail and dimension of RC frame specimens. The dimensions of RC frame were as follows: length of 2000 mm, height of 1000 mm, and crocs section of 250 × 250 mm. The water to cement ratio was 0.5 and the material proportions were 1 : 3 : 4 : 0.6 by weight of cement, sand, aggregate, and water, respectively. The average compressive strength of concrete at 28 days was 240 Mpa.

3.2. Test Monitoring Using AE Technique. A total of five RC frame 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 with threshold level of 45 dB for all channels in order to avoid the possibility of noise effect. The cyclic load pattern was determined. The load was applied at one at mid-span of the RC frame specimens. The load was applied in 10 kN steps at mid-span of RC frame. The load was applied from 0.5 kN

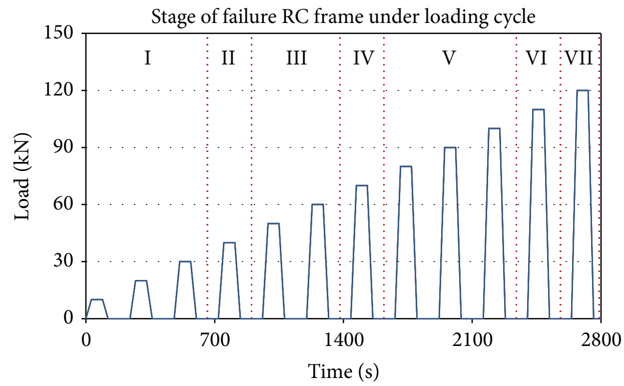

Figure 2: A typical cracks development in the RC frames specimen.

to maximum of each loading cycle (10 kN increment) and held constant for one minute. Then, the load was unloaded from maximum of each loading cycle to 0.5 kN and was held constant for 2 minutes. The test was monitored by AE throughout the test. The measurements including load, mid-span deflection, and AE data were recorded continuously during the three-point bending test. Figure 2 shows setup of an RC frame under cyclic.

4. Results Analysis and Discussion

4.1. Responses of Test RC Frame to Cyclic Loading. The RC frames described early were tested under loading cycle. Figure 2 shows a typical cracks development in the RC frames specimen. The behaviour of all RC frames under loading cycle can be divided into seven stages of failure, namely, (I) micro-cracking at the mid-span of RC frame, (II) first flexural cracks at mid-span of RC frame, (III) distributed flexural cracks at the mid-span of RC frame, (IV) first cracks at the beam-column connection zones, (V) distributed cracks at beam-column connection zones, (VI) damage localization at the beam-column connection zone, and (VII) failure at beam-column connection zone.

4.2. Relaxation Ratio. The AE data obtained in the test was used in order to carry out relaxation ratio analysis. The relaxation ratio in terms of signal strength during loading and unloading phase for all channels was calculated. Figures 3(a), 3(b), 3(c), 3(d), and 3(e) show the trend of relaxation ratio during loading cycle for all RC frames specimens. Data points represent that from loading cycle 1 to loading cycle 6 the behaviour of RC frame is in stages microcracks and cracks visible and distributed cracks in mid-span of RC frame (stages I, II, and III). The relaxation ratio is less than one. Also, from loading cycle 7 to loading cycle 12 the first crack was observed at beam-column connection until specimen failure at this region. The Relaxation ratio is greater than one.

It needs to be mentioned that relaxation ratio is based on comparison of AE activities 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 experiment work show that inversion of trend in relaxation ratio occurs when load approaches 58% ultimate load.

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 [15]. In early stages, tensile fracture cracks are primary source of AE activities. As approaching 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 [14]. In addition, in loading phase the cracks are the predominant source of AE activity while in the unloading phase the friction are sources that prevail of AE activity [5]. 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 are the primary source of AE activity. Thus, AE activity during unloading phase is dominant.

4.3. Calm Ratio Analysis. The AE data obtained in bending test was used in order to carry out calm ratio analysis. The calm ratios in terms of signals strength for all RC frames were calculated. Figure 4 shows the trend of calm ratio versus cycle number for all RC frame specimens. Data points show that calm ratio increased with increases load. Also, from loading cycle 1 to loading cycle 6 in which the behaviour of RC frame is in stages microcracks and cracks visible and distributed cracks in mid-span of RC frame (stages I, II, and III), calm ratio has low value and is less than 25%. In addition, from loading cycle 7 to loading 12 the first crack was observed at beam-column connection until specimen failure at this region. Calm ratio has a high value.

4.4. Load Ratio Analysis. The load ratios for all RC frames were calculated. Figure 5 shows the trend of load ratio versus cycle number for a RC frame specimen. Data points indicate that from loading cycle 1 to 3 load ratio is more than one and

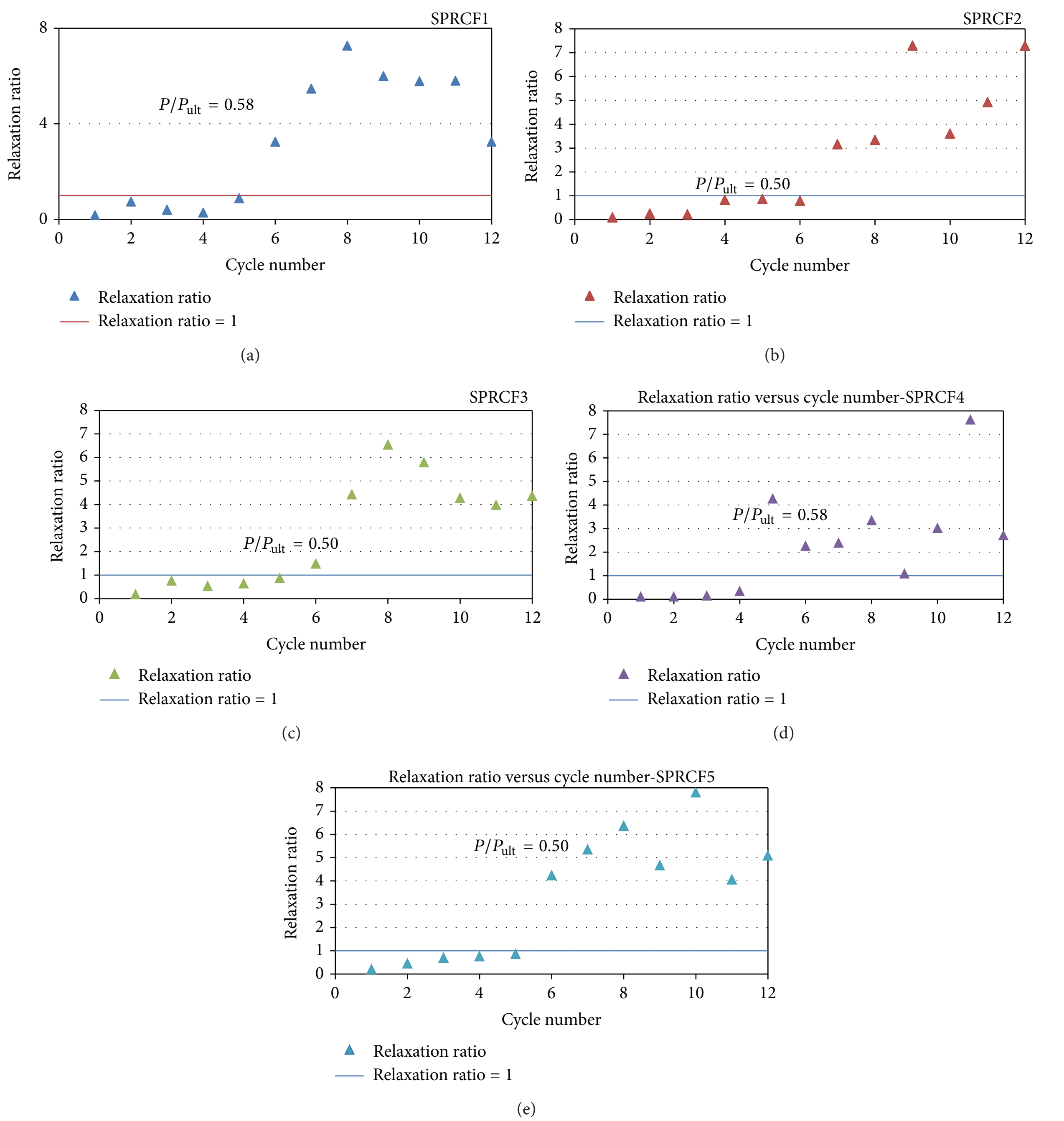

Figure 3: Relaxation ratio versus cycle number for all specimens.

from loading cycle 4 to 12, an inversion of trend in load ratio occurs and the load ratio is less than one. This change occurs when the cracks were observed. It needs to be mentioned that load ratio is based on the concept of Kaiser effect and a load ratio which was more than 1 is a criterion of a structure in good condition [5]. The results of load ratio analysis show that initial cracks associated with an inversion of trend in load ratio from more than that one to less than one. In addition, this inversion of trend in load ratio occurs when load is approaching 25% ultimate load.

4.5. Calm and Load Ratio Chart. According to NDIS 2421, damage assessment could be evaluated by using two ratios: load and calm Ratios. Calm and load ratio chart is divided into three levels of damage: low, moderate, and high. Load ratio more than 1 is a criterion of a structure in good condition [5]. Thus, an appropriate limit value for load ratio can be 1.0. In the relaxation ratio chart for RC frame, points move from a "loading dominant" to a "relaxation dominant" condition from loading cycle 6. With respect to results of relaxation ratio, an appropriate limit value for calm ratio can

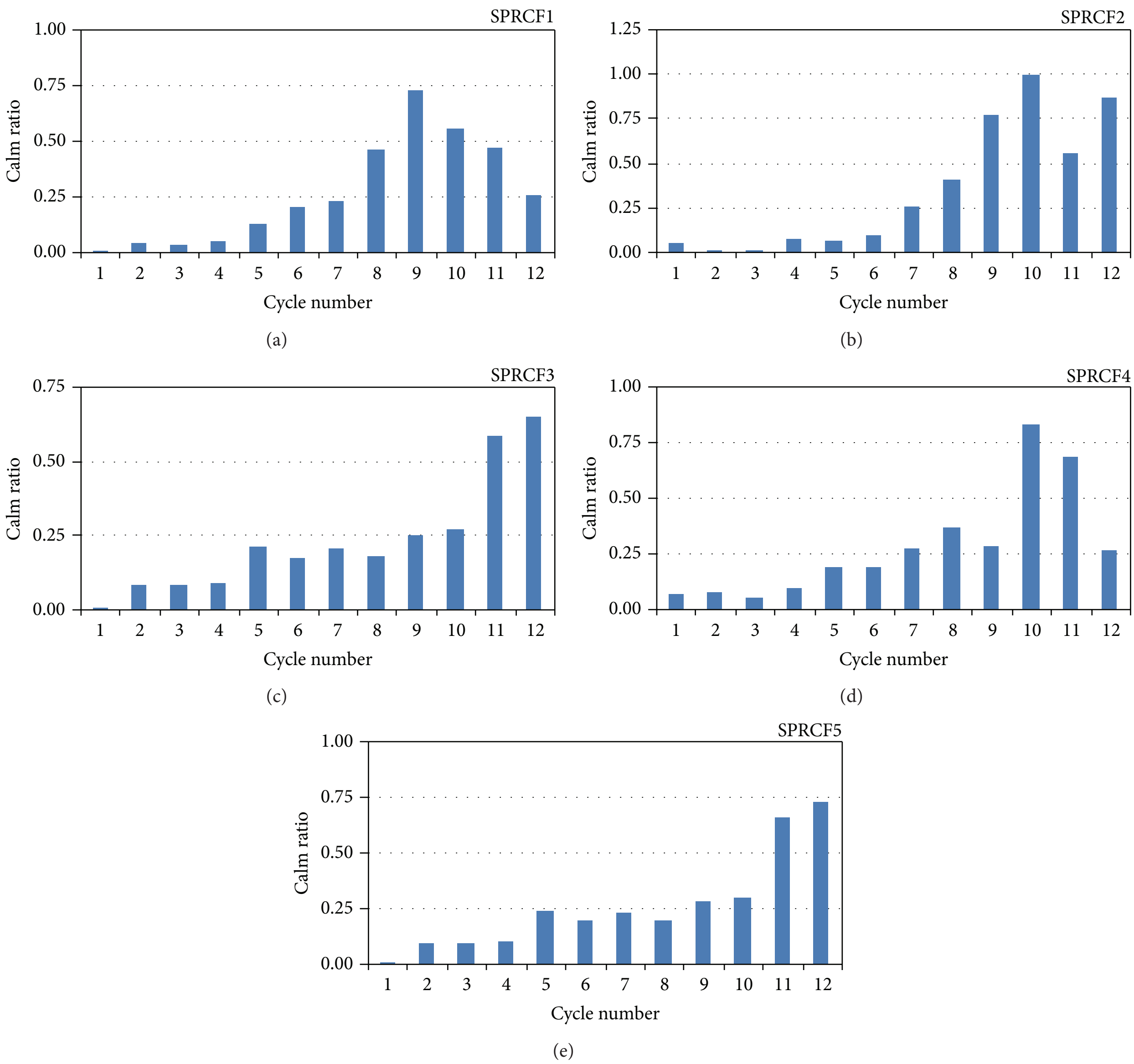

Figure 4: Calm ratio versus cycle number for all specimens.

be identified as 25%. Calm and load ratio chart was plotted with considering two limit values. Figure 6 shows calm and load ratio chart for a sample.

4.6. Proposes for a New Chart. The results of this research show that an inversion of trend in load ratio occurs when load is approaching 25% ultimate load and in stage of cracks visible at mid-span of RC frame specimen. Also, of trend in relaxation ratio occurs when load is approaching 55% ultimate load and in stage of cracks visible at beam-column connection of RC frame specimen. With respects to the results obtained from relaxation ratio and load and calm ratio indicated, a new chart is proposed by cross-plotting load and relaxation ratio. Three levels (heavy, moderate, and low) of damage in concrete structure can be identified using this chart. Figure 7(a) shows relaxation ratio versus load ratio chart. This chart was used for classification of three-level damage in the RC frame that a sample as shown in Figure 7(b).

5. Conclusions

This paper provides the results from tests on RC frame 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 load and relaxation ratio.

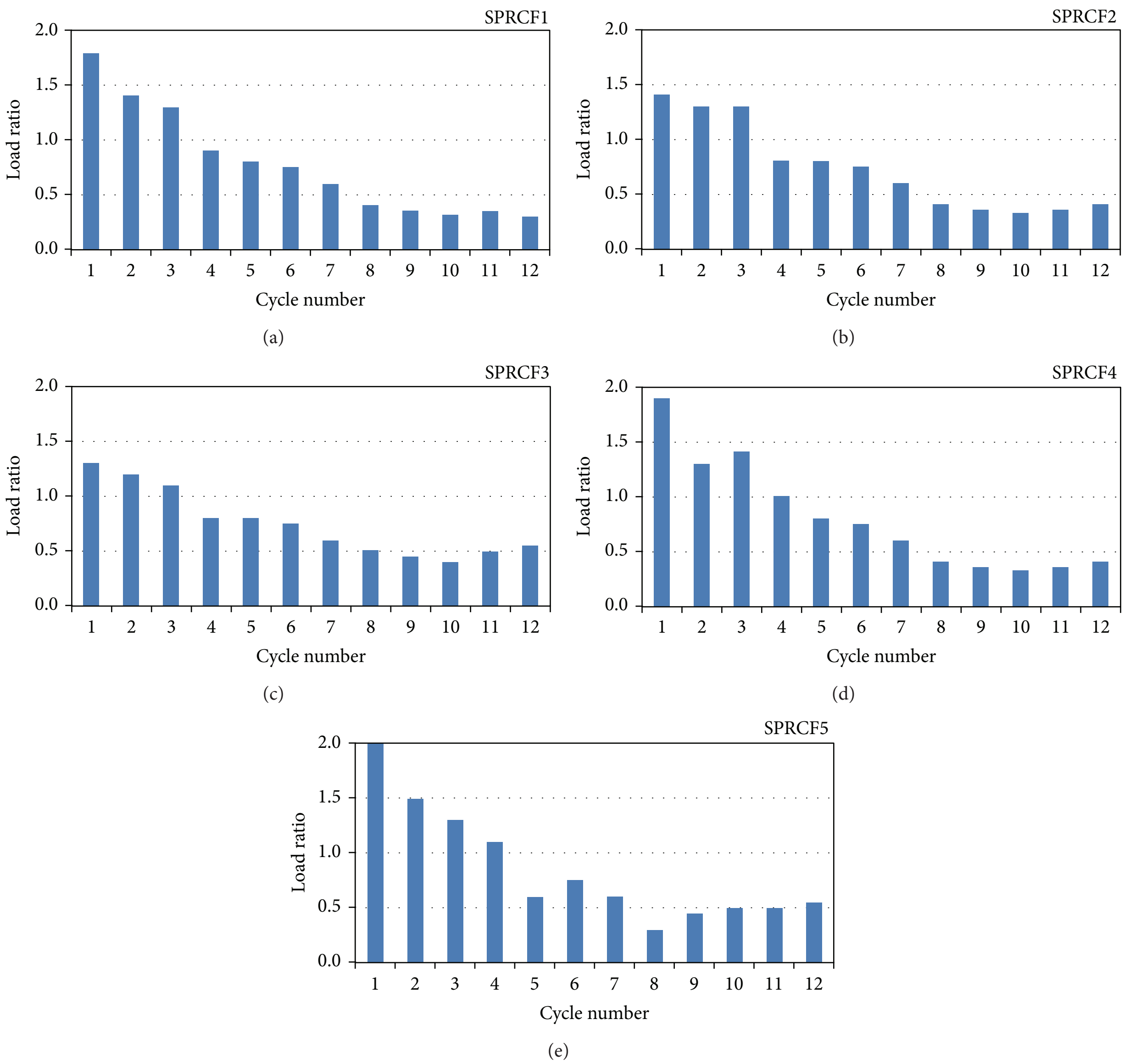

FIGURE 5: Calm ratio versus cycle number for all specimens.

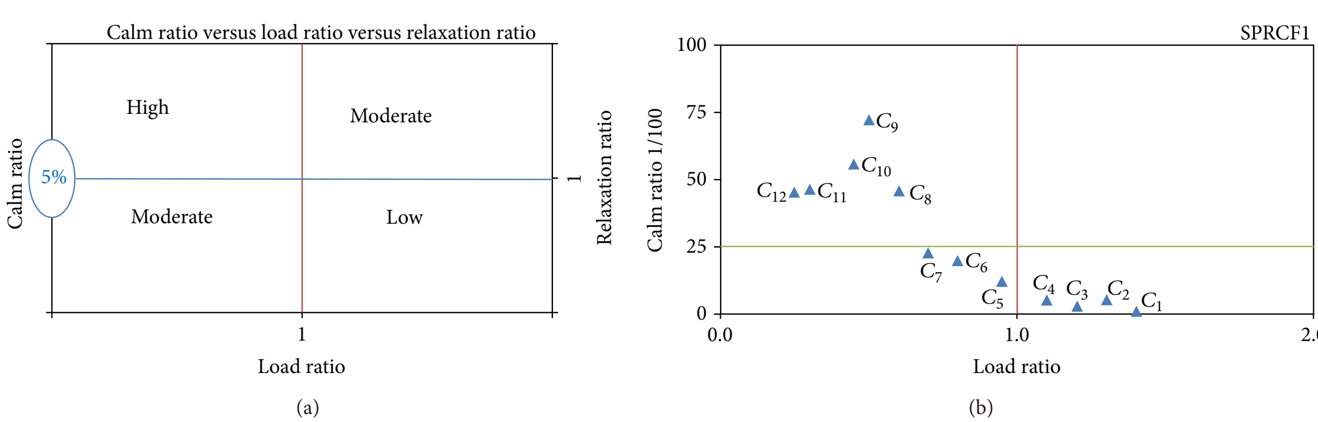

FIGURE 6: Calm ratio versus load ratio chart.

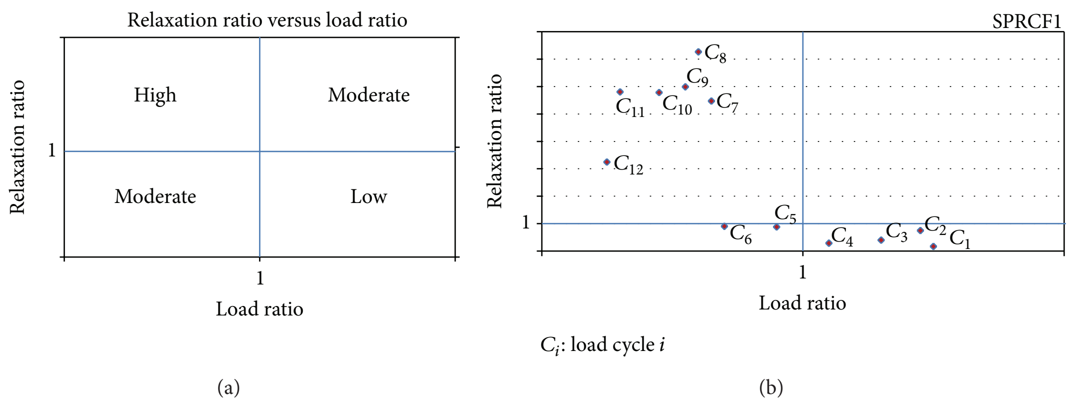

FIGURE 7: Relaxation ratio versus load ratio chart-SPRCF1.

(2) The relaxation ratio was dominated with load approaching 58% of the ultimate load.

(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 frame specimens 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.

Acknowledgment

The authors would like to thank Universiti Sains Malaysia (USM) for providing support through the short-term Grant [304/PAWAM/6039047].

References

[1] A. Nair and C. S. Cai, "Acoustic emission monitoring of bridges: review and case studies," *Engineering Structures*, vol. 32, no. 6, pp. 1704–1714, 2010.

[2] O. N. Romaniv, K. I. Kirillov, Y. V. Zima, and G. N. Nikiforchin, "Relationship of acoustic emission to the kinetics and micromechanism of fatigue failure of high-strength steel with a martensitic structure," *Soviet Materials Science*, vol. 23, no. 2, pp. 156–160, 1987.

[3] A. Pollock, "Acoustic emission inspection," in *ASM Handbook*, vol. 17, pp. 278–294, 1989.

[4] B. Muravin, *Acoustic Emission Science and Technology*, Journal of Building and Infrastructure Engineering of the Israeli Association of Engineers and Architects, Tel Aviv, Israel, 2009.

[5] S. Colombo, M. C. Forde, I. G. Main, and M. Shigeishi, "Predicting the ultimate bending capacity of concrete beams from the "relaxation ratio" analysis of AE signals," *Construction and Building Materials*, vol. 19, no. 10, pp. 746–754, 2005.

[6] Z. Liu and P. H. Ziehl, "Evaluation of reinforced concrete beam specimens with acoustic emission and cyclic load test methods," *ACI Structural Journal*, vol. 106, no. 3, pp. 288–299, 2009.

[7] A. Panjsetooni and N. M. Bunnori, "Fracture formation evaluation of reinforced concrete beam subjected to cycle loading using acoustic emission technique," *International Journal of Scientific Research in Knowledge*, vol. 1, no. 4, pp. 51–59, 2013.

[8] M. Ohtsu, M. Uchida, T. Okamoto, and S. Yuyama, "Damage assessment of reinforced concrete beams qualified by acoustic emission," *ACI Structural Journal*, vol. 99, no. 4, pp. 411–417, 2002.

[9] X. Luo, H. Haya, T. Inaba, T. Shiotani, and Y. Nakanishi, "Damage evaluation of railway structures by using train-induced AE," *Construction and Building Materials*, vol. 18, no. 3, pp. 215–223, 2004.

[10] T. Shiotani, D. G. Aggelis, and O. Makishima, "Global monitoring of large concrete structures using acoustic emission and ultrasonic techniques: case study," *Journal of Bridge Engineering*, vol. 14, no. 3, pp. 188–192, 2009.

[11] S. C. Lovejoy, "Acoustic emission testing of beams to simulate SHM of vintage reinforced concrete deck girder highway Bridges," *Structural Health Monitoring*, vol. 7, no. 4, pp. 329–346, 2008.

[12] Z. Liu, *Evaluation of Reinforced Concrete Beams Using Cyclic Load Test, Acoustic Emission and Acousto-Ultrasonics*, ProQuest, 2007.

[13] E. Proverbio, "Evaluation of deterioration in reinforced concrete structures by AE technique," *Materials and Corrosion*, vol. 62, no. 2, pp. 161–169, 2011.

[14] C. U. Grosse and M. Ohtsu, *Acoustic Emission Testing*, Springer, 2008.

[15] W. M. McCabe, R. M. Koerner, and A. E. J. Lord, "Acoustic emission behavior of concrete laboratory specimens," *Journal of the American Concrete Institute*, vol. 73, no. 7, pp. 367–371, 1976.