Relationship between acoustic emission signal strength and damage evaluation of reinforced concrete structure: Case studies

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Abstract—**Relationship between acoustic emission (AE) signal strength and damage evaluation has been reviewed. Several case studies have been referred to get information on that relationship. The notion or any opinion relates to the case study also had been discussed. Reviews of AE signal strength relate to damage evaluation of reinforced concrete structure and other materials are significantly useful for newly researchers.**

Keywords-acoustic emission; signal strength; reinforced concrete

I. INTRODUCTION

The development of advanced technology on damage evaluation had an impact in structural health monitoring part. It promises reliable and effective monitoring either locally or globally. One of the sensitive and passive [1] methods for above purpose is acoustic emission (AE) technique. It is also one of the non-destructive testing (NDT) methods that have been used widely in assessment of a structure. Passive NDT involves the monitoring acoustic or visual changes in a structure under certain load conditions with the hope that a defect will reveal itself naturally [2]. Carpinteri et al. [3] stated that this technique has proved to be highly effective especially to assess and measure the damage phenomena taking place inside a structure subjected to mechanical loading. It was proved by De Rosa et al. [4] that AE is capable for real time monitoring [5] over the whole material volume and high sensitivity to any process generating stress wave. Hence, it suites with the meaning of AE that is defined as the class of phenomenon whereby transient elastic waves are generated by a rapid release of energy from localized sources within a material, or the transient elastic waves generated [6].

In the analysis of damage detection, there are two methods normally used to analyse the output either by conventional (parameter based) or quantitative (signal based) [7, 8]. The analysis based on signal strength is related with the sensor voltage, resolution and time; which is one of the signal based analysis method. Under mechanical test, Xu [2] has represented relationship between signal strength and damage with the combination of applied load, signal strength against time with unit of kN, pVs and second (sec.), respectively. The outcome shows that it can give appropriate assessment of damage integrity of prestressed concrete structures. The same style of analysis also has been used by Liu [9] for RC beams under cyclic load test, to find correlation with the damage level of concrete specimens. Various approaches have been used in AE data analysis to relate the signal strength such as signal strength against duration (μsec), hits versus signal strength and cumulative signal strength versus load. Those approaches were represented by Carey [10] on analysis of failure mechanisms in carbon fibre reinforced polymer materials and it can be used for analysis of reinforced concrete (RC) structure. Otherwise, Ridge and Ziehl [11] has presented signal strength versus time and cumulative signal strength against elapsed time.

Based on AE characteristics of fibre reinforced plastic (FRP) composites, Ativitavas et al. [12] concluded that the cumulative AE signal strength with respect to the increased level of applied load should correspond with the cumulative number of fibre breaks or other failure mechanisms. The amplitude of 74 dB can be used as a boundary between the hits from fibre breakage and non fibre breakage based on the cumulative plot of the remaining hits versus load coinciding with the cumulative signal strength against load plot.

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Many ways have been used for damage evaluations that are related with signal strength. It can be strictly taking from the raw data that has been recorded by AE software and then analysed it, earlier calm ratio has been defined by Ohtsu [13] as the ratio of the total number of AE hits cumulated during the unloading divided by the total number of AE hits cumulated during unloading. Later, it was modified by substituting the cumulative signal strength to the total number of hits to calculate the calm ratio and defined as cumulative signal strength during unloading per cumulative signal strength during the loading [9, 14]. Then, relaxation ratio also has been used that related with signal strength. Ridge and Ziehl [11] were presented Cumulative Signal Strength (CSS) for damage evaluation of FRP strengthened RC beams. A new method based on signal strength was developed by Xu [2] adaptation from Hamstad et al. [15] on cumulative moment.

This case study primarily focuses on the damage evaluation using signal strength. The notion or any opinion relates to the case study also discussed. Reviews of AE signal strength pertaining to damage evaluation of reinforced concrete structure and other materials are significantly useful for the convenience of the readers.

II. SIGNAL STRENGTH BACKGROUND

A damage evaluation based on AE signal can be developed in many ways as well as signal strength. In mathematical definition by Physical Acoustic Corporation (PAC) [16], signal strength defined as the integral of the rectified voltage signal over the duration of the AE waveform packet. It is sometimes referred as relative energy which relates to the energy amount released by the material or structure. It is also a function of both the amplitude and duration of the signal [2]. Signal strength is independent of gain and calculated over the whole AE signal dynamic range. As represented by PAC based on sensor voltage (Vs) the value can range from 3.05pVs (1 count) to 13.01mVs with the resolution of 3.05pVs (at 1 MHz or greater sample rate) and is an absolute parameter.

Generally, the signal is normalized to 1MSPS which is equal to 1µsec. Thus, above threshold level it can be represented as summation of Vs by 1 per 1MHz or as follows:

$$\text{Signal strength} = \sum Vs \times 1/1MHz \qquad (1)$$

It means that Vs resolution equal to 3.05µV for 16 bits and 1µsec multiplied 3.05µV is 3.05 pVs. The AE signal strength has been developed by Fowler [7] as new direction in testing and represents as follows:

$$E_t = \frac{1}{2}\int_{t_1}^{t_2} f_+^2(t)\,dt - \frac{1}{2}\int_{t_1}^{t_2} f_-^2(t)\,dt \qquad (2)$$

Where f_+ is positive signal envelope function and f_- is negative signal envelope function. Meanwhile t_1 and t_2 are represented as time at first and last threshold crossing, respectively.

However, calm ratio from hit to signal strength has been represented in different approach [9, 14]. This is due to the total number of hits may be affected by time control of loading and unloading, which is hard to be controlled precisely for in-situ load test. Thus the cumulative signal strength (CSS) is substituted for the total number of hits to calculate the calm ratio. According to Liu and Ziehl [14], calm ratio is related to crack closure during unloading; which this differs slightly from other investigations where AE activity has been used in place of signal strength. It was calculated for the second load cycle of each loadset.

Calm ratio = (Cumulative signal strength during the unloading portion) / (Cumulative signal strength during the loading portion) (3)

Relaxation ratio is also given the same meaning as calm ratio and defined as the following equation; but it differs where energy has been used in place of signal strength.

CSS refers to the addition of the signal strength of each hit over time and focus on the amount of AE activity generated during reloading as compare to during previous loading, whereas average signal strength refers to the average signal strength value of the hits recorded over a given time period.

Relaxation ratio = (Average signal strength during unloading) / (Average signal strength during loading) (4)

CSS load ratio is a combination between cumulative signal strength and load ratio. It is calculated for each load set and was evaluated during the loading phase of the twin load cycles. It is shown in equation below:

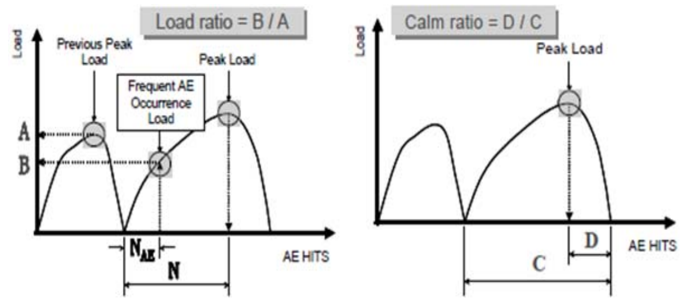

Figure 2. Definitions of load ratio and calm ratio in a cyclic loading [17].

CSS load ratio = (CSS during reloading) / (CSS during previous reloading) (5)

Fig. 2 is represented the definition of load ratio and calm ratio in a cyclic loading for classification of damage level.

Signal strength moment (SSM) has been developed by Xu [2], it is the extension from the concept of using a time weighted approach for analysing the AE activity during load holds in composite materials developed by Hamstad et al. [15].

The concept that has been established by Hamstad et al. [15] known as cumulative event rate moment. It is defined as "the summation over the hold period of the quantities produced by multiplying the number of first (per event) hits (i.e. the number of events detected) at a given sensor during a fixed time interval by the time elapsed from the beginning of the load hold, to quantify AE behaviour during the hold" as defined in equation (6).

$$\text{The Cumulative Moment},\ M = \sum_{i=1}^{N} t_i N_i \qquad (6)$$

Were t_i is the time from beginning of the hold to the ith time interval and N_i is the number of events occurring in interval i. Thus SSM for the load hold is defined as:

$$SSM = \sum_{i=1}^{n} t_i S_i \qquad (7)$$

Where n is the total number of hits occurring during the load hold and S_i is the signal strength occurring in the ith hit. In SSM, AE activity occurring during holding of load is given more weight than AE activity occurring immediately after accomplishment of the held load. This is based on assumption that sustained (or increasing) emission over time is indicative of a beam that is experiencing continued damage under the sustained load. A constant or accelerating rate of AE activity occurring during a hold would characterize a beam in which internal load-resistance mechanisms are shifting due to ongoing damage. Thus, greater SSM value indicates a beam that is experiencing continued internal distress at a certain load level.

In order to make the method less dependent on the characteristics of specific sensors, an evaluation criterion based on the SSM ratio recorded during a second (reload) load hold to the SSM during a first load was evaluated. The same time length of less than or equal to 240 seconds for two load holds was used for evaluation. The ratio expressed as a percentage shown in equation (8).

SSM Ratio = (SSM of the second hold period)/(SSM of the first hold period) x 100% (8)

This method was considered during load holds owing to several reasons. Firstly signal strength is a function of both the amplitude and duration of signal, which makes signal strength a better measure of total AE than other parameters. Secondly using AE data from a load hold minimizes the influence of loading or unloading rate. Lastly is the hypothesis that having a larger proportion of AE activity occurring later after load application is a sign of increased material damage.

III. Case Studies

A. *Case Study 1: Signal Strength versus Time by Xu [2]*

In order to assess the integrity of RC concrete by means of AE technique, four beams were tested in flexure under four-point-load. All specimens were subjected to cyclic load testing (CLT) at 10 different steps or cycles and 24 sensors were coupled on one side of the beam surface. For each group of load sets consisted of two cycles. For instance load set (LS) 1-2 consisted of cycle 1 and cycle 2. In this paper only one beam would be considered and designated as STD-M-C. During monitoring, AE and CLT data were collected simultaneously in one test sequence. Then signal strength versus time superimposed with the load cycles for selected beam has been represented in Fig. 3.

The condition of beam can be visualized as shown in Figs. 3 and 4. The black line shows a plot of applied load or cyclic load types against time. The red dotted shows the AE signal strength versus time and the blue line is cumulative signal strength versus time. At first load set, some AE activities attributed to the initial friction at the support were observed at above figure, this is typical phenomenon for first load. However the following load cycles the AE activities decreased and seemingly faded away for a few cyclic loads. This is due to AE activity was limited during uncracked beam. Since the first crack appeared at load set 5-6, it was accompanied by huge amount of AE activities.

However, it turns to reduce after that. At this stage refers to Fig. 3, no further discussion was reported by author due to cracks opening and closing, so new cracks have been developed. Then it was jumped at final load set, where the sharp AE activities increased and accompanied a rapid growth in cracking. This condition is particularly happened during the application of loads higher than those previously applied and during the unloading stage. Using AE testing, the indication of cracks can be represented well prior to first crack observed as shown in Fig. 3, where the AE activities have rapid increased at applied load of 133kN (30 kips). It shows that the onset of development of internal microcracking in the material and cannot be seen through naked eyes. The first noticeable cracks can be observed at applied load of 141kN (31.7 kips). Thus, AE testing is capable to predict forthcoming of cracks in the specimen earlier than detection by visual inspection.

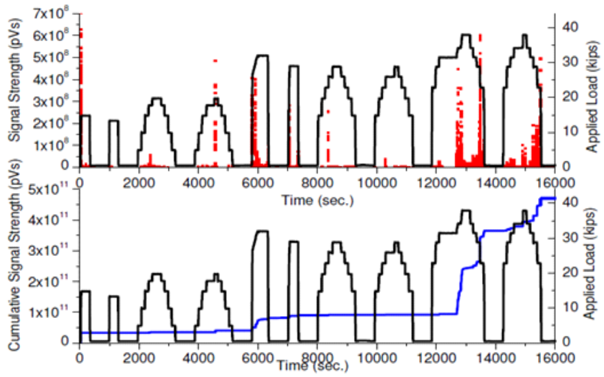

Figure 3. Load and signal strength versus time for beam STD-M-C

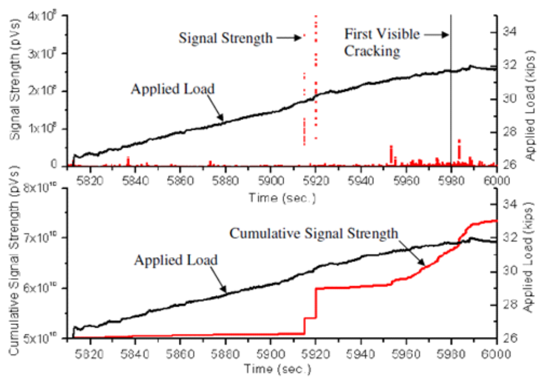

Figure 4. Load and signal strength versus time on cycle 5 for beam STD-M-C

It is suggested that the amount of signal strength at rapid increased should be taken under consideration. If the signal strength amount at particular time can be determined and the same sequence for other beams, it is going to be a good approach or indication on development of crack. It might be, with good correlation between sizes of cracks, behaviour of the materials at particular point, and AE signal strength can be used to develop a new approach for better prediction of future crack. Even all those things quite complicated, it might give a clue for future research with relate to AE.

B. Case Study 2: Signal strength moment (SSM) ratio by Xu [2]

The summary of SSM ratio evaluation is shown in Table 1. For beam STD-M-B, the values of SSM for the first three cycles were close to zero. At load set 7-8, it increased to 2.8% corresponded to the actual flexural cracking load. Then it increased rapidly at final load set with 4.9%.

The values of SSM were fluctuated for beam STD-M-C; similar to the result that has been reported in Case Study 1. The SSM ratio of 2.7% corresponded to the actual flexural cracking load occurred at load set 5-6. No SSM value was observed for the following load set and it increased to 4.3% at the last load set. The SSM values and ratios are depicted in Fig. 4 for pre-damaged beam. This implies that the damage levels of prestressed concrete beams can be qualified by the proposed criterion based on the SSM ratio is equal to or greater than 4% as an indicator the prestressed concrete beam experience of heavy damage.

Despite SSM method sounds good for damage evaluation under cyclic loads, the applicability of this method for other types of mechanical test should be taken under consideration. The applicability of this method under dynamic test without hold time is questionable. For instance, under fatigue test, generally the load is applied continuously, where the loading and unloading process is relied on the frequency has been set prior to test, apparently has no hold time. However, due to new technique in damage evaluation, it needs comprehensive study especially under load without hold time. As recommendation, it can be used as a gap for future research with little modification by ignoring the dependency of the hold time as well as under fatigue test. However, it would not promise well triumph on the finding.

TABLE I. Summary of SSM ratio Evaluation Results

Beam	**Load set number (%)**				
	1-2	***3-4***	***5-6***	***7-8***	***9-10***
STD-M-A	6	4.2	6.8	4.1	15.1
STD-M-B	0.4	0.0	0.8	2.8	4.9
STD-M-C	0.9	0.0	2.7	0.0	4.3
STD-M-D	1.3	2.6			

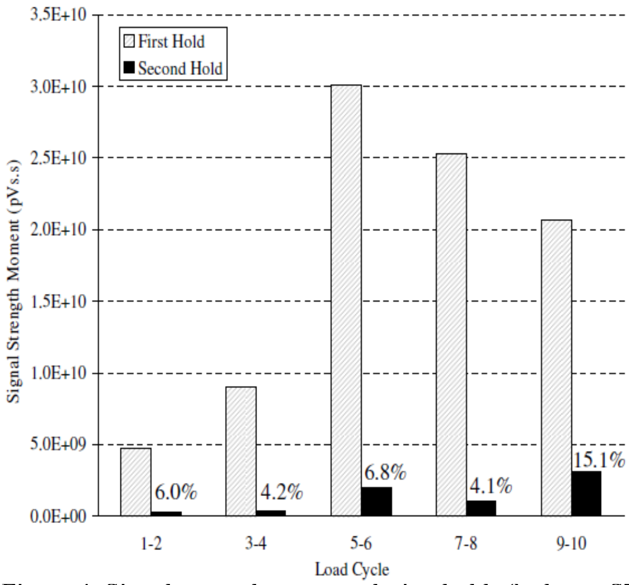

Figure 4. Signal strength moment during holds for beam STD-M-A

C. Case Study 3: Calm ratio, relaxation ratio and CSS ratio by Liu [9]

All the ratios used by Liu [9] are modification from using average energy proposed by Ohtsu et al.[13], Colombo [18] and Ridge and Ziehl [11] for calm ratio, relaxation ratio and CSS ratio to signal strength, respectively. These types of evaluation method have been used for reinforced concrete beams for normal concrete and self-consolidating concrete (SCC) subjected to four point bending. CLT has been applied throughout the test to give the failure mode of flexure and shear.

In this study the calm ratio has divided into three loads levels, based on by percentage of ultimate capacity; lower end (< 20%), intermediate (between 20% and 80%) and higher end (> 80%). It found that when the load below 20% the trend of calm ratio is difficult to establish due to inadequate of AE activity. At higher than 80%, the steel yields and unable to return to the initial position after unloading and AE decreased; hence the calm ratio also decreases.

The two ends of load levels can be neglected due to an actual operation that the lower end would not be considered and in service structure would not be operated at higher loading level when yielding of reinforcement occurs. In evaluation criteria, if the calm ratio is greater than 1, it can be considered that the structure has been seriously damaged as shown in Fig. 5.

The relaxation ratio shows similar trend to the calm ratio. However, 1.0 is not suitable indication for evaluation criterion due to several reasons and it needs standardization evaluation and the ratio is not recommended for shear specimen.

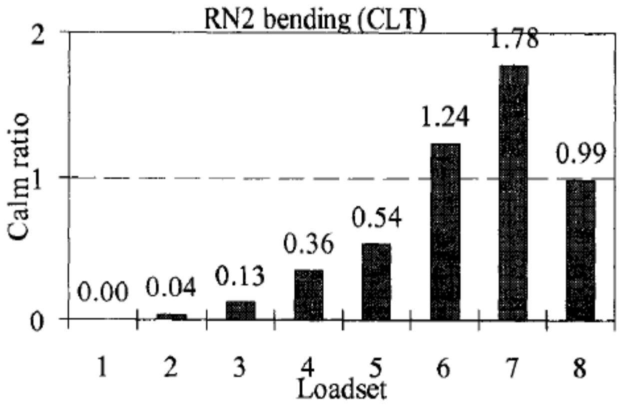

Figure 5. Calm ratio for flexure specimen

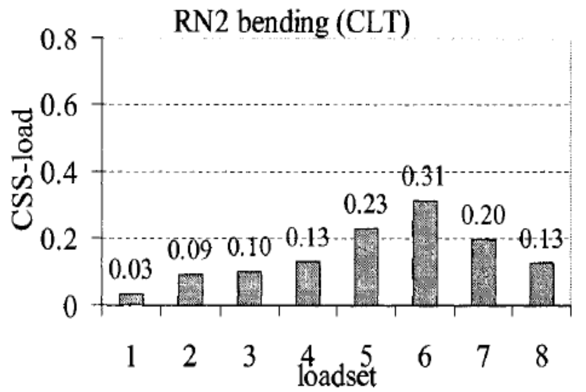

Figure 6. CSS load ratio for flexure specimens

In fact, CSS is based on the AE activities are relying on the severity of damage during reloading phase. The CSS ratio increased with the damage growth before the structure yield and decreased after yielding as shown in Fig. 6. Ridge [11] recommended CSS ratio equals 0.4 for medium scale specimen. The value differs for flexure specimen to be 0.3 (normal concrete) and 0.25 (SCC). However, the value is more reasonable for shear specimen of 0.35.

It can be concluded that, all the evaluation criterion can be used as an indicator for damage evaluation as well as damage levels.

IV. CONCLUSION

All information in this paper can be used as a guideline for AE study that relate to analysis part. Damage in concrete can be evaluated using AE signal strength analysis. Graph of signal strength versus time, beam condition can be visualized. AE testing also is capable to predict forthcoming of cracks in the specimen earlier than detection by visually inspection. Then SSM ratio greater than 4% can be used as an indicator the prestressed concrete beam of heavy damage.

Calm ratio, relaxation ratio and CSS ratio that relate with signal strength show different damage evaluation criterion. However, CSS ratio for shear specimen shows reasonable value than flexure specimen.

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REFERENCES

[1] G. R. Kirikera, V. Shinde, M. J. Schulz, A. Ghoshal, M. J. Sundaresan, R. J. Allemang, and J. W. Lee, "A structural neural system for real-time health monitoring of composite materials," Structural Health Monitoring, vol. 7, pp.65–83, 2008.

[2] J. Xu, "Nondestructive evaluation of prestressed concrete structures by means of acoustic emissions monitoring," Ph.D Thesis, Auburn Alabama, 2008.

[3] A. Carpinteri, G. Lacidogna, G. Niccolini, and S. Puzzi, "Critical defect size distributions in concrete structures detected by the acoustic emission technique," Meccanica, vol. 43, pp. 349–363, 2008.

[4] I. M. De Rosa, C. Santulli, and F. Sarasini, "Acoustic emission for monitoring the mechanical behaviour of natural fibre composites: A literature review," Composite: Part A, 2009.

[5] A. Nair, and C. S. Cai, "Acoustic emission monitoring of bridges: review and case studies," Engineering Structures, vol. 32, pp. 1704–1714, 2010.

[6] ASTM, "Standard guide for determining the reproducibility of acoustic emission sensor response," Non Destructive Testing Standard, 2005.

[7] N. Md Nor, N. Muhamad Bunnori, A. Ibrahim, S. Shahidan, and S. N. Mat Saliah, "An observation of noise intervention into acoustic emission signal on concrete structure," IEEE 7th International Colloquium on Signal Processing and Its Applications, 2011.

[8] N. Md Nor, N. Muhamad Bunnori, A. Ibrahim, S. Shahidan, and S. N. Mat Saliah, "An investigation on acoustic wave velocity of reinforced concrete beam in-plane source," IEEE 7th International Colloquium on Signal Processing and Its Applications, 2011.

[9] Z. Liu, "Evaluation of reinforced concrete beams using cyclic load test, acoustic emission and acousto-ultrasonics," Ph.D Thesis, University of South Carolina, 2007.

[10] S. A. Carey, "Acoustic emission and acouto-ultrasonic signature analysis of failure mechanisms in carbon fibre reinforced polymer materials," Ph.D Thesis, University of South Carolina, 2008.

[11] A. R. Ridge, and P. H. Ziehl, "Evaluation of strengthened reinforced concrete beams: cyclic load test and acoustic emission methods," ACI Structural Journal, vol. 103, pp. 832–841, 2006.

[12] N. Ativitavas, T. J. Fowler, and T. Pothisiri, "Identification of fiber breakage in fiber reinforced plastic by low amplitude filtering of acoustic emission data," Journal of Nondestructive Evaluation, vol. 23, pp. 21–36, 2004.

[13] M. Ohtsu, M. Uchida, T. Okamoto, and S. Yuyama, "Damage assessment of reinforced concrete beams qualified by acoustic emission," ACI Structural Journal, vol. 99, pp. 411–417, 2002.

[14] 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, pp. 288–299, 2009.

[15] M. A. Hamstad, J. W. Whittaker, and W. D. Brosey, "Correlation of residual strength with acoustic emission from impact damage composite structures under constant biaxial load," Journal of Composite Materials, vol. 26, pp. 2307–2328, 1992.

[16] P. Kalyanasundaram, C. K. Mukhopadhyay, S. V. Subha Rao, "Practical acoustic emission," Alpha Science, 2007.

[17] A. A. Shah, and Y. Ribakov, "Effectiveness of nonlinear ultrasonic and acoustic emission evaluation of concrete with distributed damages," Materials and Design, vol. 31, pp. 3777–3784, 2010.

[18] N. Muhamad Bunnori, "Acoustic emission techniques for the damage assessment of reinforced concrete structures," Ph. D Thesis, Cardiff University, 2008.

[19] P.A.C., "User's manual for SAMOS AE system," Physical Acoustic Coorporation, vol. 2, 2005.

[20] M. Shigeishi, S. Colombo, K. J. Broughton, H. Rutledge, A. J. Batchelor, and M. C. Forde, "Acosutic emission to assess and monitor the integrity of bridges," Construction and Building Materials, vol. 15, pp. 35–49, 2001.

[21] 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, pp.746–752,2005.