# DAMAGE EVALUATION OF REINFORCED CONCRETE BEAM UNDER DYNAMIC LOADING BASED ON PIEZOELECTRIC TRANSDUCERS

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In this paper, the piezoelectric transducers are used to detect the damage of reinforced concrete beams under dynamic loading. The signal of piezoelectric sensors pasted on the surface of reinforced concrete beam is separated and reconstructed based on the wavelet packet analysis, and the full waveform acoustic emission (AE) signals which are caused by fracture are obtained. Then, the damage index relied upon the accumulative duration of AE signal is established for the quantitative damage assessment of concrete beam. In addition, the character of AE signal in crack and yield stage is analyzed and the surplus stiffness of reinforced concrete beam is evaluated after circle dynamic loading. The results shows that, the AE signal can be extracted effectively through the wavelet packet analysis; AE accumulative duration can depict the damage of concrete structure under dynamic loading better than other AE parameters; the surplus of capacity of reinforced concrete beam can be evaluated by the AE accumulative duration.

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ABSTRACT: In this paper, the piezoelectric transducers are used to detect the damage of reinforced concrete beams under dynamic loading. The signal of piezoelectric sensors pasted on the surface of reinforced concrete beam is separated and reconstructed based on the wavelet packet analysis, and the full waveform acoustic emission (AE) signals which are caused by fracture are obtained. Then, the damage index relied upon the accumulative duration of AE signal is established for the quantitative damage assessment of concrete beam. In addition, the character of AE signal in crack and yield stage is analyzed and the surplus stiffness of reinforced concrete beam is evaluated after circle dynamic loading. The results shows that, the AE signal can be extracted effectively through the wavelet packet analysis; AE accumulative duration can depict the damage of concrete structure under dynamic loading better than other AE parameters; the surplus of capacity of reinforced concrete beam can be evaluated by the AE accumulative duration.

## 1 INTRODUCTION

Structural damage caused by unexpected disasters like earthquakes is usually during a dynamic process and how to evaluate the carrying capacity of the structure after the dynamic loading destruction is still a problem unsolved. Acoustic emission (AE) is the transient elastic wave of the partial strain caused by material fracture and defects. Also, Acoustic emission is a phenomenon associated with the process of concrete damage (Ji, 1996) and a historical memory of the structural damage. Therefore, it is quite feasible to use AE signals sampled by the piezoelectric sensor to evaluate the damage degree under the dynamic destruction.

Many researchers have done lots of work to study the relationship between AE signals and damage. Ohtsu (2001, 2004) proposed acoustic emission rate theory and established the relationship between AE events and strain level. Ji (1996, 2000, 2003) analyzed the AE mechanism, acquired the AE pattern of damage in concrete, and established the coupling relationship between AE parameters of concrete material and strain and stress. Zhu (2008) realized quantitative damage evaluation of concrete based on AE rate theory.

The currently existing damage evaluation method of concrete is aimed at plain concrete. Unlike plain concrete, the structural destruction of reinforced concrete has both crack stage and yield stage. The damage in the yield stage cannot be ignored under dynamic

destruction. How to evaluate the surplus carrying capacity of reinforced concrete after entering the yielding stage with AE technology is a problem to be solved in the current study.

Firstly the dynamic damage test of reinforced concrete beam is conducted. Then, the piezoelectric sensor signals pasted on the surface of reinforced concrete beam are separated and the AE signals are acquired. The characteristic parameters used by AE cumulative duration and the relationship between the parameters and the damage are proposed, and the quantitative evaluation of the surplus carrying capacity of reinforced concrete under dynamic damage is realized by using AE technology based on piezoelectric transducers.

## 2 EXPERIMENT

The compression strength of concrete in the reinforced concrete beams are 30MPa and 50MPa, respectively. The span of beam is 2.5m with the cross section of 150mm*250mm (the reinforcement of the cross section is shown in Figure 1). The longitudinal steel bars are HRB335 with the diameter of 18 mm. The stirrups are HPB 235 steel bar with the diameter of 6.5 mm and the interval of 200 mm. The ratio of longitudinal reinforcement is 1.6% and of stirrup is 0.22%.

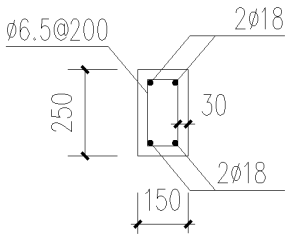



Figure 1 Section of reinforcement concrete beam

The loading device used in the experiment is 2500KN concrete dynamic tri-axial test machine. Data acquisition equipment is the PXI virtual instruments from NI company and the sampling frequency is set to 100kHz/s. The piezoelectric ceramic (PZT) are attached to the surface of the beams as the transducers, which are pasted on the central axis which is 400 mm away from both ends. The arrangement of loading device and of sensors is shown in Figure 2.

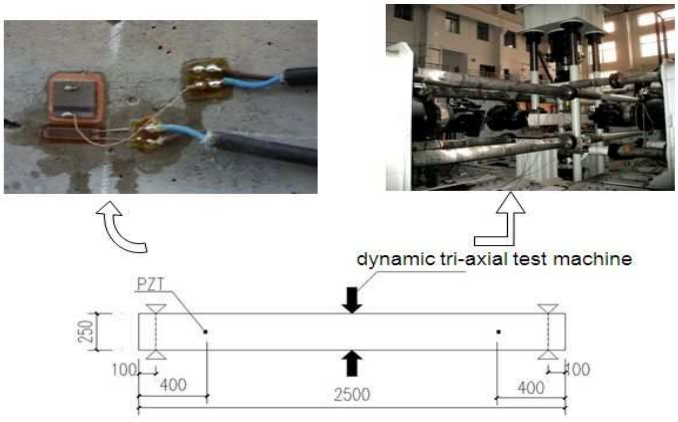



Figure 2 Loading device of beams and arrangement of sensors

The dynamic loading of beams was conducted using monotonic, cyclic and two shear-span ratio respectively. The loading speed is 30mm/s (Specimen condition shown in Table 1). Data of loading and cross displacement are acquired synchronously when loading.

Table 1 Experiment Specimen Condition

| Specimen No. | Loading Pattern | Shear-span ratio | Concrete Strength |
|---|---|---|---|
| Specimen 1 | Monotonic | 3.3 | C30 |
| Specimen 2 | Monotonic | 3.3 | C50 |
| Specimen 3 | Cyclic | 5 | C30 |
| Specimen 4 | Cyclic | 5 | C50 |
| Specimen 5 | Cyclic | 3.3 | C30 |
| Specimen 6 | Cyclic | 3.3 | C50 |

## 3 RESULTS ANALYSIS AND DISCUSSIONS

### *3.1* Retraction of AE signal

The piezoelectric transducer pasted on the surface of beam can not only accept the AE signal, but also receive the signal caused by the change of internal force on the plane of polarization. However, the frequency of signal caused by the change of internal force is much lower than the one from AE signal. In addition, the piezoelectric transducers are inevitably affected by noise which distributes all over the frequency domain. Therefore, it is necessary to reduce noise and reconstruct the AE signal from sensor signal. In this paper, the AE signal is reconstructed based on wavelet package analysis. The signal is analyzed by wavelet packet for ten layers with db25 wavelet package basis for which is characterized by short support, orthogonality and slickness, then applying threshold de-noising method (Zhao, 2007) to reduce the noise. The AE signal is required by reconstructing the wavelet packet details coefficients expect the one in (10,0) layer. The original sensor signal is as shown in Figure 3 and the AE signal is as shown in Figure 4.

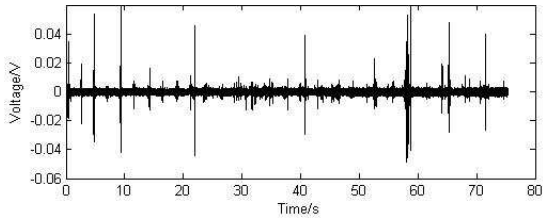



Figure 3 the original sensor signal

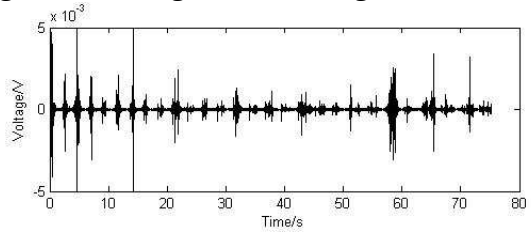



Figure 4 AE signal retracted from piezoelectric transducers

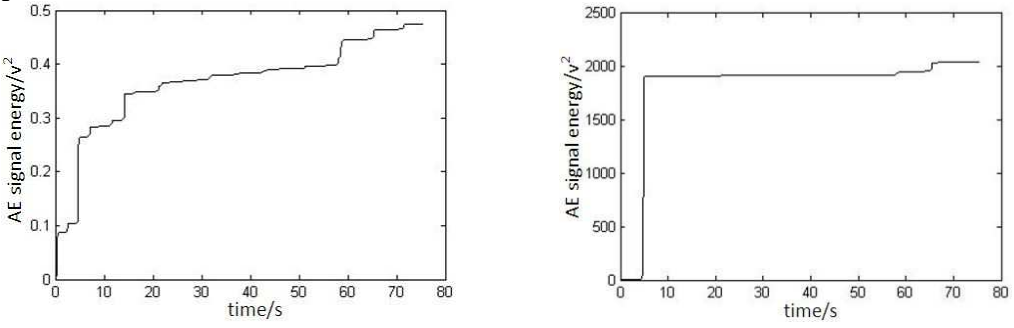
### 3.2 Confirmation of AE parameters

Concrete damage is a cumulative process which is not reversible. Therefore, the AE cumulative parameters can better describe the damage process. The commonly used AE cumulative parameters include AE events, hits, cumulative release of energy and so on. During the dynamic loading process, there are several AE sources, and the damage process is quite transitory, and that may even cause a fast loading and the cumulative number of AE only being one. This will cause different sources AE overlap phenomenon. Therefore, the dynamic damage structure of multi-damage points may lead to the incomprehensive statistical cumulative parameters by using AE events and ring count as AE parameters.

The energy of AE signals is of great importance to material fracture and damage evaluation. The study in the literature (Eric, 2002) shows that the AE signal energy has correlation with fracture energy, and it doesn't have much correlation with the inner aggregate friction and other energy loss mechanism. The energy expression of AE signal (Harris, 1977) is shown in Equation (1).

$$E(i) = \int_{t_0}^{t_1} V_i(t)^2 \, dt \quad (1)$$

$i$ is the $i$th sensor channel, $t_0$ and $t_1$ are the starting and ending time of the recorded voltage, respectively; $V_i(t)$ is the voltage value. As the distance from the sensor varies, AE signals emitted by different AE sources have different energy levels (Muralidhara, 2010). The closer the distance from the sensor, the less the elastic wave attenuation in concrete and the bigger the AE signal amplitude. On the contrary, the more distance from the emission sources, the smaller the AE signal. During dynamic loading, AE events emitted by different sources will not on the same energy level. From Figure 5 we can see the accumulative energy is different for the distance between AE souses for different sensors. Therefore, the cumulative energy cannot be directly used as AE parameters.




From sensor a From sensor b

Figure 5 AE signal energy from sensor a and sensor b

To make AE signals better describe the AE ability of the components on the same level and at the same time, the cumulative AE duration is used as AE activity parameter in this paper, which can eliminate the impact of the distance between AE sources and the sensor. As a result, the parameters of different AE sources can be on the same level. In addition, in terms of the total number of AE, the dynamic loading damage of reinforced concrete can be described more accurately.

### 3.3 Analysis of the AE characteristics of dynamic loading reinforced concrete beams in monotonous loading

Acoustic emission is the associated phenomenon of cracking, and AE signal is the memory of cracking history. Cracking phenomenon occurs mainly in the crack stage and yield stage in reinforced concrete beams. At different load-carrying stages of beams, damage mechanisms are different, and so are AE characteristics. Figure 6 is load curve of specimen 1, which is synchronous with AE signal in Figure 7. In the monotonic loading with the loading speed being 30mm/s, the process of fracture in the crack stage is continuous. However, the process of fracture in the yield stage is not continuous. Therefore, AE signal begins to show its discontinuous characteristics. There is also a disturbance phenomenon at the yield stage in Figure 6, which also shows that the process of fracture in the yield stage is discontinuous.

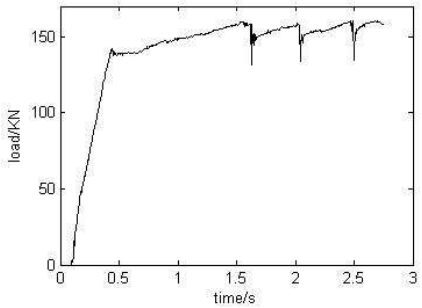



Figure 6 load curve of specimen 1

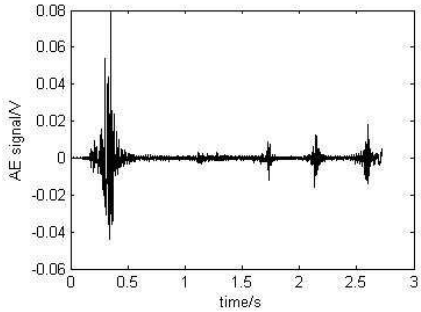
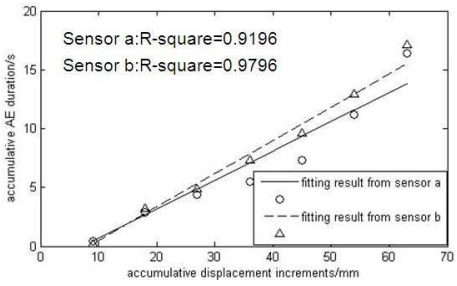


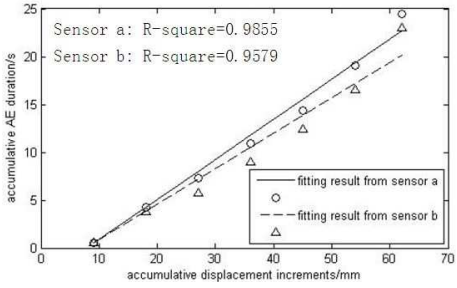

Figure 7 AE signal of specimen 1

### 3.4 The evaluation of surplus stiffness of reinforced concrete beam in circle loading

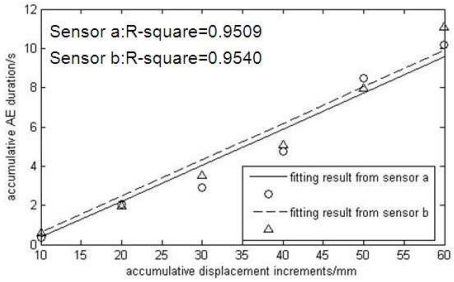
Compared with monotonic loading, the displacement of beams in the cyclic loading is no longer in a single direction, but the loading of upward-and-downward reciprocation. Because of the existence of Kaiser effect, AE is no longer obvious in the already experienced displacement. Figure 8 includes the accumulative AE duration (represented by $t_d$) at different accumulative displacement increments in the same direction (represented by $\Delta s$) and the regression curve. It can be considered as an approximate linear relationship between the accumulative cross displacement increments and the accumulative AE duration at the end time of AE event.

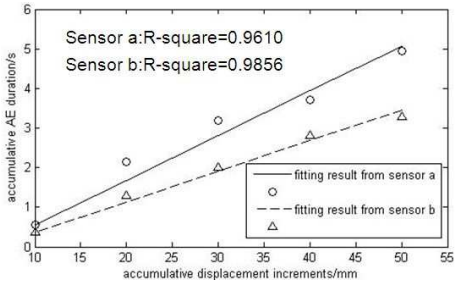



Specimen 3




specimen 4




Specimen 5

specimen 6

Figure 8 accumulative AE duration in different Δs

Figure 9 is the ideal load-displacement curve in which $F_{cr}$ and $s_{cr}$ represent the cracking loading and cracking displacement respectively, $F_y$ and $s_y$ represent the yielding load and yielding displacement respectively, and $F_u$ and $s_u$ represent the loading and displacement when the beams are being damaged. $k_{cr}$,$k_y$ and $k_u$ represent the stiffness of concrete beams when the beams are in the stages of cracking, yield and damaging, respectively.

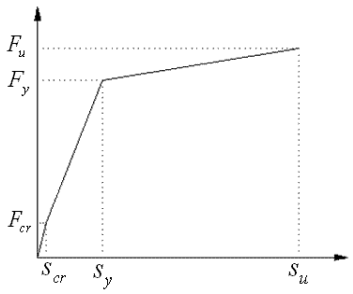



Figure 9 The ideal displacement-load curve

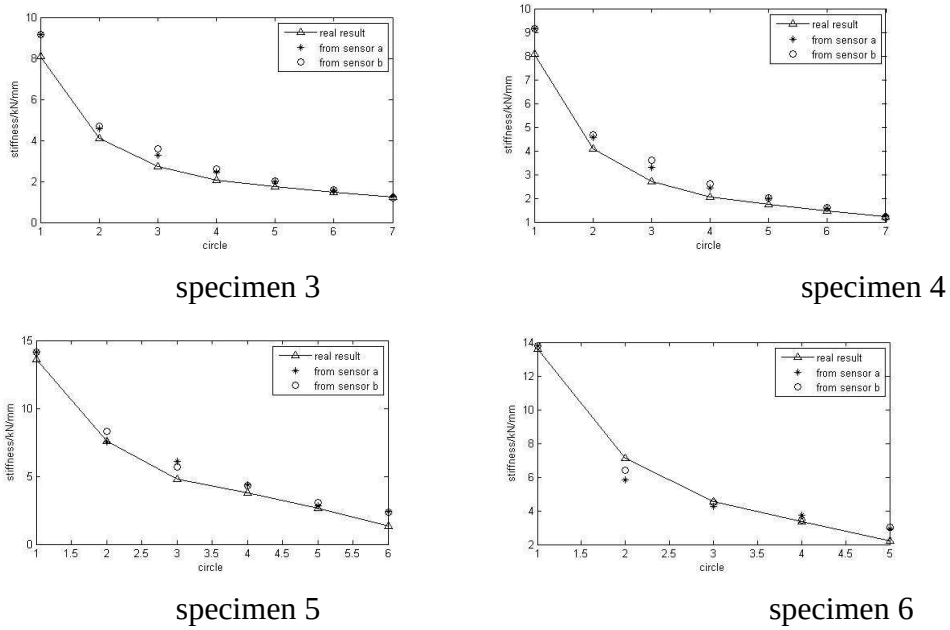
The stiffness of components is calculated as Equation (2).

$$k(s)=\begin{cases}\dfrac{F_{cr}}{s_{cr}} & s\le s_{cr}\\ \dfrac{A_{cr}}{s}+B_{cr} & s_{cr}<s\le s_y\\ \dfrac{A_y}{s}+B_y & s_y<s\le s_u\end{cases} \quad (2)$$

Where, $A_{cr}=\left[F_{cr}-\dfrac{s_{cr}(F_y-F_{cr})}{s_y-s_{cr}}\right]$, $B_{cr}=\dfrac{F_y-F_{cr}}{s_y-s_{cr}}$, $A_y=\left[F_y-\dfrac{s_y(F_u-F_y)}{s_u-s_y}\right]$, $B_y=\dfrac{F_u-F_y}{s_u-s_y}$

Put the approximative relationship between $t_d$ and $\Delta s$ to Equation_2, and the stiffness after the degradation of the reinforced concrete beams can be calculated. Figure 10 is the stiffness in the maximum displacement of each circle calculated through td and the

real one. It can be seen that the calculated results have correspondence with the real one.




specimen 3 specimen 4

specimen 5 specimen 6

Figure 10 The stiffness in the maximum displacement every week of the cyclic loading of reinforced concrete beams

## 4 CONCLUSION AND DISCUSSION

Through wavelet analysis, the piezoelectric transducer signal pasted on the surface of concrete can be seperated and the AE signals can be effectively retracted. Under dynamic loading, using AE cumulative duration as the AE activity parameter can eliminate the negative impact caused by different distance of AE sources and the sensor, and can better describe the AE ability of the target material. In the crack and yield stages of the dynamic loading of reinforced concrete beams, since the damage mechanisms are different, AE characteristics are not identical; fracture in the yield stage has the discontinuous phenomenon, so AE is discontinuous. In this experiment, with the loading speed of 30mm/s, there is an approximative linear relationship between the accumulative cross displacement increments and the AE accumulative duration at the end time of each AE event, by which the degraded stiffness of reinforced concrete beams in the cyclic loading can be calculated. The further research will focus on assure this relationship and the relationship between td and damage theoretically, which is essential to use td to evaluate the damage under dynamic destruction.

*References*

Eric, NL and Baillon L. 2002. Experiments to relate acoustic emission energy to fracture energy of concrete. *Journal of Engineer Mechanics*, 7, 698-702.

Harris, D.O. and Bell RL. 1977. The measurement and significance of energy in acoustic emission testing. *Experimental Mechanics*, 17, 347-353.

Ji, HG and Cai, MF. 2003. Coupling constitutive relation between AE parameter and stress-strain and its application. *Chinese Journal of Rock Mechanics and Engineering*, 22(2), 227-231. (in Chinese)

Ji, HG, Jia, LH and Li, ZD. 1996. Study on the AE-model of concrete damage. *Acta Acustica*, 21(4), 601-608. (in Chinese)

Ji, HG, Zhang, TS and Cai, MF. 2000. Experimental study on concrete damage by dynamic measurement of acoustic emission. *Chinese Journal of Rock Mechanics and Engineering*, 19(2), 165-168. (in Chinese)

Muralidhara S, Prasad, BKR and Eskandari H. 2010. Fracture process zone size and true fracture energy of concrete using acoustic emission. *Construction and Building Materials*, 24, 479-486.

Ohtsu, M and Watanabe, H. 2001. Quantitative damage estimation of concrete by acoustic emission. *Construction and Building Materials*, 15, 217-224.

Suzuki, T and Ohtsu, M. 2004. Quantitative damage evaluation of structural concrete by a compression test based on AE rate process analysis. *Construction and Building Materials*, 18, 197-202.

Zhao, XY and Li, HN. 2007. Noise control for health monitoring signal of a civil structure based on PZT sensors. *Journal of Vibration and Shock*, 26, 137-139. (in Chinese)

Zhu, HP, Xu, WS and Chen, XQ. 2008. Quantitative concrete-damage evaluation by acoustic emission information and rate-process theory. *Engineering Mechanics*, 25(1), 186-191. (in Chinese)