Materials and Structures (2010) 43:1183–1186
DOI 10.1617/s11527-010-9639-z

RILEM TECHNICAL COMMITTEE

Recommendation of RILEM TC 212-ACD: acoustic emission and related NDE techniques for crack detection and damage evaluation in concrete*

Test method for damage qualification of reinforced concrete beams by acoustic emission

RILEM Technical Committee (Masayasu Ohtsu)**

1 Scope

Acoustic Emission (AE) techniques have been investigated in concrete engineering for more than a half century [1]. Nowadays, results of AE research are going to be applied to practical use, not only in concrete structures, but also in masonry structures [2, 3]. This is because the increase of aging structures and disastrous damages due to recent earthquakes urgently demands for maintenance and retrofit of reinforced concrete structures in service.

Reinforced concrete structures in service could deteriorate due to heavy traffic loads and fatigue. In order to assess the damage levels of the structures by AE, one criterion based on the Kaiser effect is proposed. The damages of such reinforced concrete beams in service as bridges, docks and buildings are qualified, by simply applying cyclic loading and monitoring AE activity. This recommendation is referred to the existing standards and codes [4–14], of which the newest versions shall be cited.

2 Definition of technical terms

In addition to terms defined in *RILEM recommendation*, “measurement method for acoustic emission signals in concrete”, the following terms are defined.

(a) *AE count and hit*: One AE transient signal detected by AE sensors and processed by a given AE channel. Normally, AE counts imply the number of times when the signal amplitude exceeds the threshold. They also are rigorously named ring-down counts, or simply referred to as counts. The number of hits is obtained by event-counting and corresponds to that of AE waves detected at one channel

---

*The text presented hereafter is a draft for general consideration.

Comments should be sent within 6 months of publication to the TC chairman, Prof. Masayasu Ohtsu, Graduate School of Science and Technology, Kumamoto University, 2-39-1 Kurokami, Kumamoto 860-8555, Japan. Phone: +81-96-342-3542, Fax: +81-96-3423507, E-mail: Ohtsu@gpo.kumamoto-u.ac.jp.

**This recommendation was developed by a work group within RILEM TC212-ACD under the leadership of Mr. Masayasu Ohtsu, Japan.

TC-Membership:

Chairman: Masayasu Ohtsu, Japan.

Secretary: Tomoki Shiotani, Japan.
Members: M. Shigeishi, T. Kamada, S. Yuyama, T. Watanabe, T. Suzuki, Japan; J. G. M. van Mier, T. Vogel, Switzerland; C. Grosse, R. Helmerich, Germany; M. C. Forde, U.K.; A. Moczko, Poland; D. Breysse, France; S. A. Ivanovich, Russia; A. Sajna, Slovenia; D. Aggelis, Greece; G. Lacidogna; Italy.

RILEM Technical Commitee 212-ACD
(Masayasu Ohtsu) (✉)
Graduate School of Science and Technology, Kumamoto University, 2-39-1 Kurokami, Kumamoto 860-8555, Japan
e-mail: Ohtsu@gpo.kumamoto-u.ac.jp.

(b) *AE activity*: Occurrence of AE hits or counts under stressed conditions in concrete.
(c) *Kaiser effect*: If stresses are applied, removed and then reapplied to a material or a structure, little AE activity is observed until the maximum load of the previous stage is surpassed. This irreversibility or stress memory is called the Kaiser effect and can be applied to estimate the magnitude of the previous stress to which the structure has been subjected.
(d) *Felicity ratio*: The ratio of the load at which emissions start to the previous maximum load. In concrete, the Kaiser effect is not wholly valid. When the level of stress becomes high, AE activity is observed below the previous maximum load. This behavior is called the Felicity effect

3 Requirement for measuring system

For detection of AE signals, AE sensors shall be sensitive enough to detect AE signals generated in a concrete member, taking acoustic coupling into consideration. Sensitivity calibration of AE sensors shall be performed in advance by employing the standard source. AE sensor shall be also robust enough against temperature change, moisture condition and mechanical vibrations in the environments. AE sensor shall be attached at proper locations to cover the target area.

In advance to the test, attenuation properties of the target structure shall be estimated, by employing the standard source. Based on this information, sensor location shall be determined so as to keep appropriate sensitivity.

The internal noise of the amplifier shall be inherently low and less than 20 μV (26 dB for 0 dB = 1 μV) as the peak voltage converted by input voltage. The amplifier shall be also robust enough against the environmental conditions and be protected properly.

The frequency range shall be determined prior to the measurement, taking into account the performance of AE sensor and the amplifiers. A suggested range in concrete is from several kHz to several hundreds of kHz, because such higher frequency components as over 1 MHz readily attenuate in concrete. For selection of the frequency range, it is suggested to refer to *RILEM recommendation* “measurement method for acoustic emission signals in concrete” mentioned above.

For signal analysis, AE parameters of AE count or AE hit shall be detected and processed. The measurement system shall be able to obtain time information along with AE data. In addition, such external parameters as load, strain and so forth are preferably recorded in the system, which might be equipped with an enough memory to record the data measured. It is preferable that all the data recorded are analyzed digitally by computer.

4 Environmental noises

In advance to AE measurement, the noise level shall be estimated. Then, counteract against external noises, wind, rain, sunshine and so forth shall be conducted to decrease the noise level as low as possible. In the case that the noises have similar frequency contents, amplitudes to AE signals or sources of the noises are unknown, characteristics of the noises shall be estimated prior to the measurement. Based on this result, separation of AE signals from the noises shall be achieved. In this respect, the use of filters is applicable after determining the proper frequency range. Normally, to eliminate mechanical noises due to vibrations, traffics and so forth, a high-pass filter over several kHz is useful. Elimination of electrical noises is made by a low-pass filter over several 100 kHz.

5 Test procedure

5.1 Basics

The period of the measurement shall be prescribed, depending on the conditions of a target structure or member, possibly in service. Sensitivity of AE measurement system shall be conducted routinely by employing the standard source. Variation within the channels shall be less than 3%. The threshold level for counting shall be set as low as possible, depending on the level of the noises. In concrete, total amplification by the pre-amplifier and the main amplifier is suggestive to be 60 dB gain or more.

AE activity is evaluated from the number of AE counts or hits. The onset of AE activity is identified at the time when more than ten counts over the threshold are continuously observed under loading.

5.2 Failure modes of reinforced concrete beams and AE activity [15]

Two failure modes are known. One is the bending-mode failure. In the beginning of loading, tensile cracks are nucleated at the bottom of a moment span due to bending moment. When the beam is either under-reinforced for bending or fully reinforced against diagonal shear failure, steel reinforcement in the axial direction yields and tensile cracks are further nucleated and then propagate upward. AE counts or hits in a beam of the bending-mode failure increases acceleratedly with the increase in loading. The other is called the shear-mode failure. In the case that the beam is over-reinforced or little reinforced against diagonal shear failure, final failure results from the sudden generation of diagonal shear cracks in the shear span without yielding of reinforcement. AE counts or hits are observed at constant rate because the reinforcement withstands until the final failure. Right before the final stage, diagonal shear cracks are observed without any precursors along with the rapid increase in AE counts or hits. Since AE activity in a damaged beam is of main concern to apply the recommended practice, these two failure modes should be taken into consideration in the case of AE monitoring.

With respect to AE activity in the reinforced concrete beam, a relation between crack-mouth opening displacement (CMOD) and the presence of the Kaiser effect is known. The Kaiser effect disappears in the either case that the values of CMOD due to bending-mode failure become wider than 0.1–0.2 mm or that the shear-mode failure is observed. It is noted that the values of CMOD over 0.1 mm approximately correspond to the serviceability limit of the reinforced concrete beam.

5.3 Load ratio and calm ratio

To quantify the Kaiser effect in AE monitoring, the Felicity ratio was proposed [16]. Provided that the Kaiser effect is present, the ratio should be equal to 1.0. It was also reported that the ratio became lower than 1.0 due to the damage repeated in the reinforced concrete beams. In principle, the concrete structures undamaged are statically stable with high redundancy. Because the Kaiser effect is closely associated with structural stability, the ratio could become larger than 1.0 in a very sound structure. Due to damage accumulation, the ratio decreases lower than 1.0, generating AE events even at lower loading levels than before. Thus, the ratio is a good indication of the damage accumulation and structural instability. Further, AE activity during unloading is another indication of structural integrity. In the case that the structure is statically stable, AE activity is seldom observed in the unloading process.

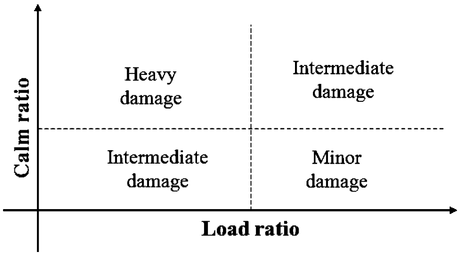

Fig. 1 Qualification of the damages by the two ratios

The ratios to estimate the Kaiser effect are defined, as follows;

(a) Ratio of load at the onset of AE activity to previous load:

$$\textit{Load ratio} = \text{load at the onset of AE activity in the subsequent loading}/\text{the previous maximum load.}$$

(b) Ratio of cumulative AE activity during the unloading process to that of the last maximum loading cycle:

$$\textit{Calm ratio} = \text{the number of cumulative AE activity under unloading}/\text{total AE activity during the wholecycle.}$$

In the practice, the damage assessment is proposed to classify the damage levels as prescribed in Fig. 1.

The classification shall be applied to AE activity under such loading as incremental, cyclic and fatigued. The particular values to classify the damages of the calm ratio and the load ratio shall be properly determined in advance to the establishment of the criterion, based on experimental data obtained at the site or in a laboratory. For example, 0.9 load ratio and 0.05 calm ratio were suggested for the classification in laboratory tests of 3 m-span reinforced concrete beams [15]. For a concrete bridge beams, 0.3–0.45 load ratio and 0.6 calm ratio were applied [17, 18]. Recently, for shorter beams than 1 m, 0.4–0.5 load ratio and 1.0 calm ratio were applied [19].

6 Documents

Documents to report the results shall contain the following articles:

(a) Date
(b) Test person
(c) Devices
(d) Measurement locations
(e) Results of system inspection before and after the setup
(f) Results of analytical data before and after the setup

References

1. Grosse CU, Ohtsu M (eds) (2008) Acoustic emission testing. Springer, Heidelberg
2. Carpinteri A, Invernizzi S, Lacidogna G (2009) Historical Brick-Madsonry subjected to Double Flat-Jack test: acoustic emission and scale effects on crack density. Construct Build Mater 23:2813–2820
3. Carpinteri A, Lacidogna G, Invernizzi S, Manuello A, Binda L (2009) Stability of the vertical bearing structures of the Syracuse cathedral: experimental and numerical evaluation. Mater Struct 42:877–888
4. European Norms (2009) EN1330-9 nondestructive testing—terminology-part 9: terms used in AE testing
5. EN 13554 Nondestructive testing-acoustic emission-general principles
6. American Society for Testing and Materials (ASTM) E1316 Standard definitions of terms relating to AE
7. ASTM E650 Standard guide for mounting piezoelectric AE sensors
8. ASTM E750 standard practice for characterizing AE instrumentation
9. American Society for Nondestructive Testing (ASNT) DGZfP-SE1 nondestructive testing: acoustic emission terms
10. ASNT DGZfP-SE3 Guide line for AE characterization during AE test
11. French Association for Standards (AFNOR) NF A09-350 nondestructive testing-vocabulary used in acoustic emission
12. European Working Group on Acoustic Emission EWGAE codes for AE examination: code I-location of discrete acoustic events
13. EWGAE Codes for AE examination: code IV-definition of terms in AE
14. Japanese Society for Nondestructive Inspection (JSNDI) NDIS 2421 recommendation practice for in situ monitoring AE of concrete structures by AE
15. Ohtsu M, Uchida M, Okamoto T, Yuyama S (2002) Damage assessment of reinforced concrete beams qualified by acoustic emission. ACI Struct J 99(4):411–417
16. Fowler TJ (1986) Experiencve with acoustic emission monitoring of chemical process industry vessels. In: Progress in AE vol III, pp 150–162
17. Colombo S, Forde MC, Main IG, Halliday J, Shigeishi M (2005) AE energy analysis on concrete bridge beams. Mater Struct 38:851–856
18. Colombo S, Forde MC, Main IG, Shigeishi M (2005) Predicting the ultimate bending capacity of concrete beams from the “relaxation ratio” analysis of AE signals. Construct Build Mater 19:746–754
19. Liu Z, Ziehl P (2009) Evaluation of reinforced concrete beam specimens with acoustic emission and cyclic load test methods. ACI Struct J 106(3):288–299