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Acoustic Emission (AE) and Related Non-destructive Evaluation (NDE) Techniques in the Fracture Mechanics of Concrete

Fundamentals and Applications

Edited by Masayasu Ohtsu

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List of contributors

F. Accornero Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Torino, Italy

D.G. Aggelis Vrije Universiteit Brussel, Pleinlaan, Brussels, Belgium

L. Calabrese University of Messina, Messina, Italy

A. Carpinteri Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Torino, Italy

A. Deraemaeker Université Libre de Bruxelles (ULB), Brussels, Belgium

C. Dumoulin Université Libre de Bruxelles (ULB), Brussels, Belgium

M. ElBatanouny University of South Carolina, Columbia, SC, USA

F. Grondin UNAM Université, École Centrale de Nantes, Nantes, France

K. Izuno Ritsumeikan University, Kusatsu, Shiga, Japan

G. Karaiskos Université Libre de Bruxelles (ULB), Brussels, Belgium

Y. Kawasaki Ritsumeikan University, Kusatsu, Shiga, Japan

G. Lacidogna Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Torino, Italy

L. Linzer University of the Witwatersrand, Johannesburg, South Africa

A. Loukili UNAM Université, École Centrale de Nantes, Nantes, France

A. Manuello Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Torino, Italy

T.E. Matikas University of Ioannina, Ioannina, Greece

L. Mhamdi University of Delaware, Newark, DE, USA

A.C. Mpalaskas University of Ioannina, Ioannina, Greece

G. Niccolini Department of Structural, Geotechnical and Building Engineering, Politecnico di Torino, Torino, Italy

K. Ohno Tokyo Metropolitan University, Hachioji-shi, Tokyo, Japan

T. Okamoto Ritsumeikan University, Kusatsu, Shiga, Japan

H. Oshita Chuo University, Tokyo, Japan

K. Otsuka Tohoku Gakuin University, Tagajo, Miyagi, Japan

E. Proverbio University of Messina, Messina, Italy

B.K. Raghu Prasad Indian Institute of Science, Bangalore, India

J. Saliba UNAM Université, École Centrale de Nantes, Nantes, France; Université de Bordeaux, Bordeaux, France

T. Schumacher University of Delaware, Newark, DE, USA

R.K. Singh Bhabha Atomic Research Centre, Mumbai, India

T. Suzuki Niigata University, Niigata, Japan

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Edited by M. Ohtsu

Preface

Toward a sustainable society, the need to extend the long-term service life of infrastructure has been evolutionally emphasized. With the increase in aging and disastrous damages in concrete structures, continuous maintenance of structures in-service has been highlighted all over the world. Because this issue is of critical importance, development of nondestructive evaluation (NDE) techniques for the inspection of concrete structures is currently in high demand. Thus, a variety of innovative NDE techniques are actively under development in concrete engineering, which are closely associated with fracture mechanics. For fundamentals and application on this subject, recent findings on acoustic emission (AE) and related NDE techniques are summarized in this book.

The contents are essentially associated with the organized session at the 8th International Conference on Fracture Mechanics of Concrete and Concrete Structures (FraMCoS-8) held in 2013 at Toledo, Spain. The organized session was to promote scientific interest and to exchange of ideas in the application and the development of AE and NDE techniques based on fracture mechanics of concrete and concrete structures.

Accordingly, the book consists of chapters associated with AE and NDE techniques including X-ray and thermography. It deals with the following subjects, following Chapter 1 Introduction: Damage evaluation in concrete, AE monitoring of crushing and fracture energies and wireless system, Identification of fracture process zone by AE, Corrosion-induced cracks and NDE for rebar corrosion, Seismology-based AE for monitoring in concrete structures, AE monitoring in concrete beams under creep, Laboratory investigation on concrete fracture using AE, Monitoring of crack propagation in RC beams using embedded piezoelectric transducers, Prediction of rebar corrosion by thermography, Estimation of concrete strength by X-ray method, Low-level AE in the long-term monitoring, Artificial neural network analysis of AE in corrosion monitoring of a post-tension concrete beam, and Continuous AE monitoring for evaluation of concrete structures.

The editor hopes that the book is useful for newcomers and practitioners in studying AE and related NDE techniques, and could contribute further to the safety and reliability of infrastructures. With respect to the human body, a medical checkup system has already been developed in Japan as the ward for a detailed medical checkup, which is well known as "the ningen (human in Japanese) dock." In order to extend the service life of the concrete structure, we propose an "infradock," so-called after "the ningen dock." Consequently, subjects presented in the book can be synthesized as major constituents of a diagnosis and prognosis procedures in the "infradock."

The editor would like to thank all contributors in this book for their continuing efforts and achievements to complete these chapters, and also acknowledge gratefully the patience and encouragement of the staff of Woodhead Publishing.

Masayasu Ohtsu

Introduction

M. Ohtsu
Kumamoto University, Kumamoto, Japan

1 Introduction

In the following chapters, we deal mostly with acoustic emission (AE) techniques. Consequently, fundamentals of AE measurement are briefly stated in relation with failure and fracture mechanics of concrete. Due to crack nucleation, AE phenomena such as elastic wave generation and propagation are observed. In order to detect AE waves, fundamentals for the measurement are summarized. Theoretically, the measuring system is formulated by applying the linear system theory. As a result, the frequency response of the system is a key issue for the measurement. Recently, the standardizations of AE tests in concrete are in progress. Thus, three recommendations by RILEM are presented.

2 Acoustic emission and fracture mechanics

Fracture in a material takes place with the release of stored strain energy, which is consumed by nucleating new external surfaces (cracks) and emitting elastic waves. The latter phenomenon is defined as acoustic emission (AE). The elastic waves propagate inside a material and are detected by an AE sensor as shown in Figure 1.

Concrete materials can be observed in the various scales from atomic structure to large-scale buildings. At the micro scale, the individual cement grains and are the complex pore structure are visible. Upon increasing the meso-scale to 10^{-3} m, individual sand and aggregate particles can be distinguished. At this scale, nucleation of micro-cracks can be identified and detected as AE phenomena. At the macro-scale, these cracks coalesce macroscopically, resulting in final failure. In the case, AE events are actively observed.

For theoretical treatment of AE, elastic waves due to cracking in a homogeneous medium are normally taken into account. Although concrete materials are not homogeneous but inhomogeneous and heterogeneous, elastodynamic theories are applicable. This is because material properties in elastodynamics are fundamentally dependent on the characteristic dimensions of materials. The dynamic heterogeneity is closely dependent on the relation between these and wavelengths of propagating waves. According to the theory of wave scattering, in the case that the wavelengths are even longer than the sizes of heterogeneous inclusions, the effect of heterogeneity

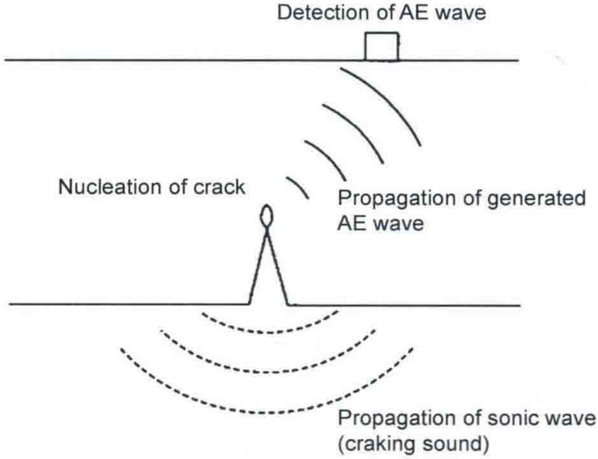

Figure 1 Detection of acoustic emission waves.

is inconsequent. In the case of AE waves in concrete, the velocities of elastic waves are over 1000 m/s. Thus, the use of frequency range up to some 100 kHz corresponds to the case where the wavelengths are longer than several centimeters. It results in the fact that concrete consisting of normal aggregate (with around 10 mm diameter) is reasonably referred to as homogeneous.

In fracture mechanics, cracks can nucleate in three distinct modes, namely tensile opening (mode I), in-plane shear (mode II) and out-of-plane shear (mode III). According to a three-dimensional (3D) lattice analysis at the meso-scale (Lilliu & van Mier, 2003), it is demonstrated that mode I plays a key role for crack extension. In addition, it is confirmed that AE technique is useful to detect prepeak mode I cracking in concrete (van Mier, 2007). So, opening cracks are to be detected as micro-cracks prior to reaching final failure. Concerning crack modes, a theoretical analysis of AE waves can provide kinematic information on mechanisms at the meso-scale. To this end, the moment tensor analysis (Ohtsu, Okamoto, & Yuyama, 1998) is applicable to classify various crack types and to determine three-dimensionally crack orientations, along with crack locations.

At the macro-scale, crack propagation due to expansive pressure was previously analyzed on the basis of linear elastic fracture mechanics and a repair strategy was investigated (Ohtsu & Yoshimura, 1998). From further investigation (Ohtsu & Yoshimura, 1997), it is found that the spalling crack normally extends in the case that the concrete cover thickness is comparable to the size of coarse aggregate and thus the surface crack is arrested by the aggregate, which is stronger or stiffer than mortar matrix. It is confirmed that these cracking behaviors are readily detected by AE measurement.

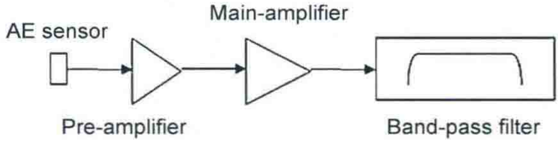

Figure 2 Acoustic emission measuring system.

3 Fundamentals of acoustic emission (AE) measurement

For AE measurement, care is needed because detection of AE signals is affected by environmental vibrations from a string wind, passersby, and a truck passing on a nearby street. Many of these problems have been eliminated with development of instrumentation systems. In updated devices, the frequency range of the measurement is normally set above that of audio or environmental noises, which are substantially minimized by grounding. Owing to advances of measuring systems, the use of a band-pass filter effectively eliminates background noises and allows meaningful tests under usual laboratory environments.

Although recent AE devices are fully digitized, detection systems are basically of analog type as shown in Figure 2. AE waves are detected by AE sensor, which converts dynamic vibrations at the surface of a material into electrical signals. Because AE signals are weak, they are normally amplified by two amplifiers of a preamplifier and a main amplifier. The signal-to-noise ratio of the devices shall be low, and the amplifiers often provide more than 1000 times gain. Lately, it is set to normally 100 times or so.

In concrete materials, the band width from several kilohertz to several 100 kHz or 1 MHz is recommended in the measurement. The frequency range of the waves could cover the inaudible range over the audible range (acoustic or lower than 20 kHz). The sonic waves higher than the audible range are defined as ultrasonic waves. Rigorously speaking, AE waves are neither ultrasonic nor acoustic. Sonic or acoustic waves are waves in air, consisting of only volumetric waves (P wave). In contrast, AE waves are elastic waves of solid in the ultrasonic range.

4 System response

AE signals are detected, as dynamic motions at the surface of a material, and are converted into electric signals by the sensor. The electrical signals are amplified and filtered. Mathematically, the system response is formulated by the linear system as,

$$g(t) = f(t) * w(t) \tag{1}$$

This implies that the sensor response $g(t)$ is obtained from the convolution (*) of the source $f(t)$ with the impulse response of the system $w(t)$. Introducing the Fourier transform,

$$G(f) = F(f)W(f) \tag{2}$$

Here $G(f)$, $F(f)$, and $W(f)$ are Fourier transforms of $g(t)$, $f(t)$, and $w(t)$, respectively.

The signals measured using AE sensors are of small magnitude compared to other methods. As a result, AE signals obtained by the sensors are very weak and have to be so amplified as to be detected and recorded. All of these influences can be assigned by different transfer functions. As a result, AE signal $a(t)$ recorded in the system are mathematically represented as,

$$a(t) = w_f(t) * w_a(t) * w(t) * f(t) \tag{3}$$

where $w_f(t)$ and $w_a(t)$ are transfer functions of the filter and the amplifiers. For characterizing AE sources theoretically, it is so important to know the weights of these functions as to eliminate their influences. In usual cases, the transfer functions of both the filter $w_f(t)$ and the amplifier $w_a(t)$ are known to be fairly flat or almost constant in the frequency domain. Eventually, it is found that the frequency response or the transfer function $w(t)$ or $W(f)$ of AE sensor significantly affects the frequency contents of AE signals.

5 Standardization of AE measurement

RILEM Technical Committee 212-ACD: Acoustic Emission (AE) and Related Nondestructive Evaluation (NDE) Techniques for Crack Detection and Damage Evaluation in Concrete was set up in 2004, and established three recommendations as follows:

5.1 Recommendation for AE measurement (Ohtsu, 2010a)

For crack detection and damage evaluation, AE phenomena are to be observed under in-service conditions. This implies that AE measurement could be conducted not only in a laboratory, but also *in situ*. Taking into account the fact, a measurement method is standardized for detecting AE signals in concrete and concrete structures.

From the definition, transient elastic waves are generated by the release of energy in concrete. These waves due to crack nucleation are referred to as AE waves, which propagate inside a material and are detected by an AE sensor as illustrated in Figure 1. AE signals are detected by AE sensor, which can convert elastic motions into electrical signals. A resonance-type AE sensor is widely employed, because it is most sensitive around the resonant frequency. It is known that a broad-band sensor has approximately

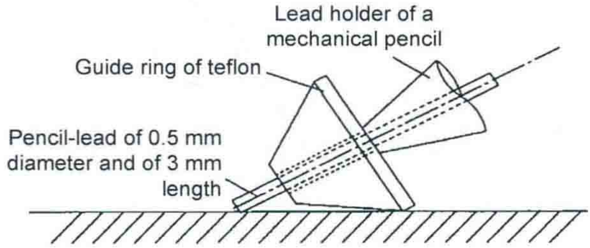

Figure 3 Acoustic emission standard source by pencil-lead (2H) break.

flat response in the target range, but is less sensitive than the resonance-type. So far, resonance-type AE sensors have been mostly applied in the frequency range of 50–250 kHz in concrete.

Sensitivity calibrations of AE sensors, as well as measuring systems, are usually performed by employing the standard source. A simulated AE source due to pencil-lead break has been defined by ASTM, ASNT, and EWGAE as listed in the references. The standard source is illustrated in Figure 3, where a guide ring is recommended to be employed. The pencil-lead break is known as Hsu–Nielsen source in AE technology (Hsu & Breckenridge, 1981; Nielsen, 1977). Sensitivity of AE channels in the system is to be checked routinely by employing the standard source. Variation within the channels shall be less than 3% in the voltage.

The gain of the amplifier is given in dB (decibels), which means the ratio of the output voltage V_o to the input voltage V_i as,

$$dB = 20 \log_{10}(V_o/V_i) \tag{4}$$

A total gain of pre- and main-amplifiers employed in concrete is 40–60 dB. The frequency range is to be determined prior to the measurement, taking into account the performance of AE sensors and systems. Selection of the frequency range is closely related to elimination of noises. In concrete, a band-pass filter between around 10 kHz and several 100 kHz up to 1 MHz is recommended.

One waveform is to be counted as one AE hit, while the cycles over the threshold level are named as AE ringdown counts (or simply "counts"). Here, the threshold is a preset voltage level, which has to be exceeded before one AE signal is detected and processed. The threshold level applied in AE measurement is usually 30–50 dB in concrete.

5.2 *Recommendation for damage qualification by AE (Ohtsu, 2010b)*

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 (Grosse and Ohtsu, 2007) is proposed. The damages of such