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Acoustic Emission Method Application at Three-Point Bending to Determine Parameters for Double-*K* Model

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Abstract. As concrete is one of the most popular building materials, it is important to know its basic properties and behaviour especially at loading. When cracks occur in concrete, released fracture energy will be proportionally transformed into the energy contained in acoustic emission. According to this physical phenomenon, acoustic emission technique provides an effective monitoring method for fracture process of concrete through generated acoustic emission. However, such monitoring is limited in qualitative evaluation of fracture process in most occasions. Quantitative interpretation of fracture process is difficult to accomplish by simply acquiring the amount of acoustic emission generated or by conducting parameter-based acoustic emission analysis. This paper investigates the use of the double-*K* fracture model and acoustic emission for prediction of load at the beginning of stable crack propagation in three-point bending tests of concrete specimens. Double-*K* model combines the concept of cohesive forces acting on the effective crack increment with a criterion based on the stress intensity factor.

Introduction

The fracture phenomena of concrete have recently attracted the attention of a large number of researchers. The fracture toughness of concrete is one of the fundamental material parameters in numerical simulation and practical designing. [1]

Acoustic emission method detects the stress waves generated from the place, where internal stress is distributed in the material. The causes of acoustic emission are structural changes, namely, micro-changes. Crack initiation and growth, crack opening and closure and dislocation movement, are possible acoustic emission sources at three-point bending tests. Acoustic emission method detects only the active changes in structure, which means that geometric discontinuities do not produce acoustic emission activity. [2,3,4]

Concrete is typical quasi-brittle material, therefore the whole fracture process of concrete can be divided into three different stages. For that reason the double-*K* fracture model is applied. This model can determine the critical crack tip opening displacement and the fracture toughness and it is capable of describing different levels of crack propagation: an initiation part, which corresponds to the beginning of stable crack growth (at the level where the stress intensity factor K_{Ic}^{ini} is reached), and a part featuring unstable crack propagation (after the unstable fracture toughness K_{Ic}^{un} has been reached). The load level value F_{ini} corresponds to the beginning of stable crack growth from an initial stress concentrator and can also be computed from initiation stress intensity factor K_{Ic}^{ini}. [5]

Acoustic emission and fracture

Theoretical application of acoustic emission method at three-point bending is introduced in Fig. 1. The first acoustic emission source is supposed to be created on the top of the notch. Therefore, the position of sensors near the notch is suitable.

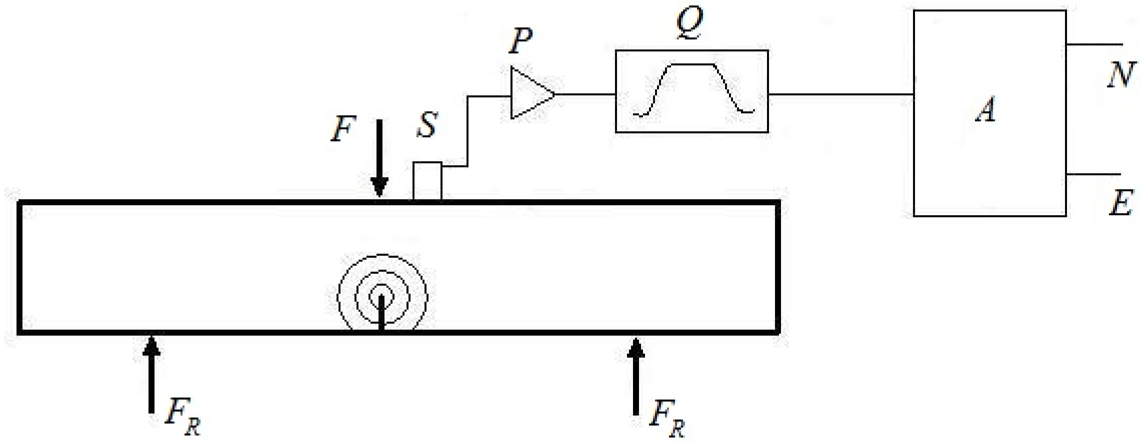

Figure 1 Application of acoustic emission method at three-point bending (F – force, F_R – reaction, S – acoustic emission sensor, P – preamplifier, Q – filter, A – acoustic emission analyser and N, E – parametric inputs as force, displacement) [6]

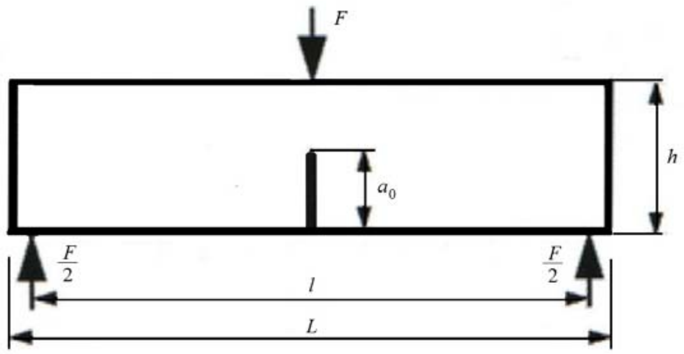

Figure 2 Three-point bending fracture test geometry

In this case fracture toughness K_{Ic}^{ini} is defined as the stress intensity factor created by the load F_{ini} at the effective crack tip and can be expressed as the resistance to the beginning of stable crack propagation. To evaluate this parameter, the following linear elastic fracture mechanics formula can be used [5]:

$$K_{Ic}^{ini} = \frac{M_{ini}}{W}\sqrt{a_0}\,F_1(\alpha_0), \text{ where } \alpha_0 = \frac{a_0}{h}, \tag{1}$$

$$M_{ini} = \frac{(qL + F_{ini})l - \frac{1}{2}qL^2}{4}, \tag{2}$$

$$F_1(\alpha_0) = \frac{1{,}99 - \alpha_0(1-\alpha_0)(2{,}15 - 3{,}93\alpha_0 + 2{,}7\alpha_0^{\ 2})}{(1+2\alpha_0)(1-\alpha_0)^{3/2}}, \tag{3}$$

where the load at the beginning of stable crack propagation, F_{ini}, is the input parameter readily obtained from the measured *F–CMOD* diagram, a_0 is the initial notch length, h and L are the specimen dimensions (height, length), l is load span, q is the self-weight of the specimen and W is the section modulus given by the following equation $W = \frac{b \cdot h^2}{6}$.

To obtain value of fracture toughness K_{Ic}^{un}, it is necessary to determine the critical effective crack length a_c corresponding to the maximum load F_{max}. Details can be found e.g. in [5].

Experimental set-up

Three-point bending tests were performed on beams with a central edge notch, the nominal dimensions of the specimens were 100 mm ×100 mm ×400 mm, the depth of the central edge notch was about 1/3 of the depth of the specimen, and the loaded span, l, was equal to 300 mm. A notch was cut before testing. During tests an acoustic emission activity was recorded. The guard sensor eliminated mechanical and electrical noise.

Acoustic emission system DAKEL with software XEDO has been applied for continuous monitoring of concrete structure loading. Four acoustic emission sensors were placed on specimen surface.

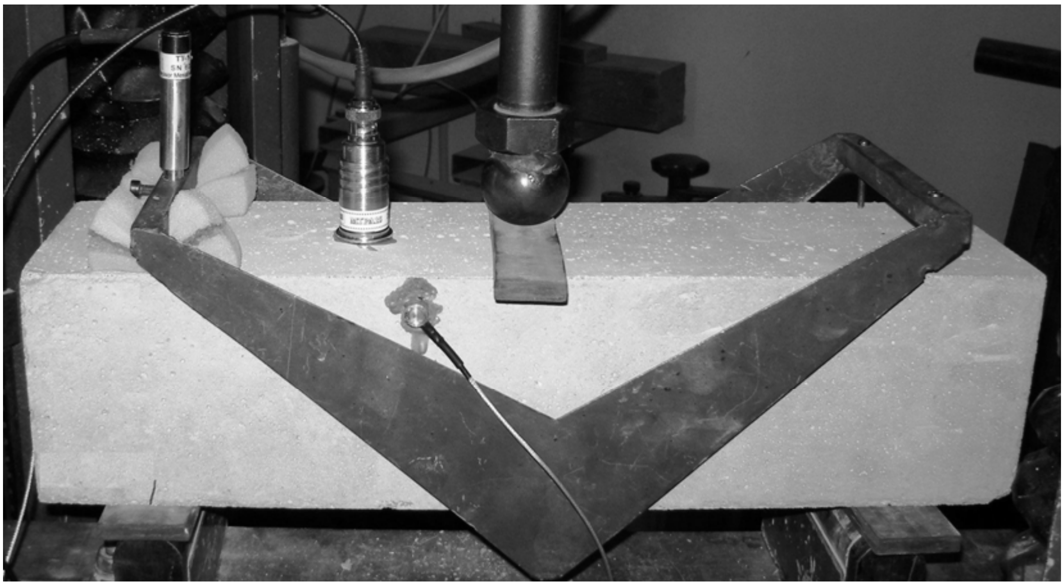

Figure 3 Experimental set-up

Applied force increased by 6 N/s as shown in Fig. 4 (5).

Results

One of the input data of double-*K* fracture model are two forces which can be deducted from *F–CMOD* diagram. The first force, respectively maximum load, F_{max}, can be clearly read from Fig. 4 or 5. *F–CMOD* diagram was not recorded as during tests, the acoustic emission method could help to obtain the load at the beginning of stable crack propagation, F_{ini}. According to Fig. 5, the first crack could be expected at forces 530 N, or 740 N, or 1.6 kN, which is where the acoustic emission activities were detected first.

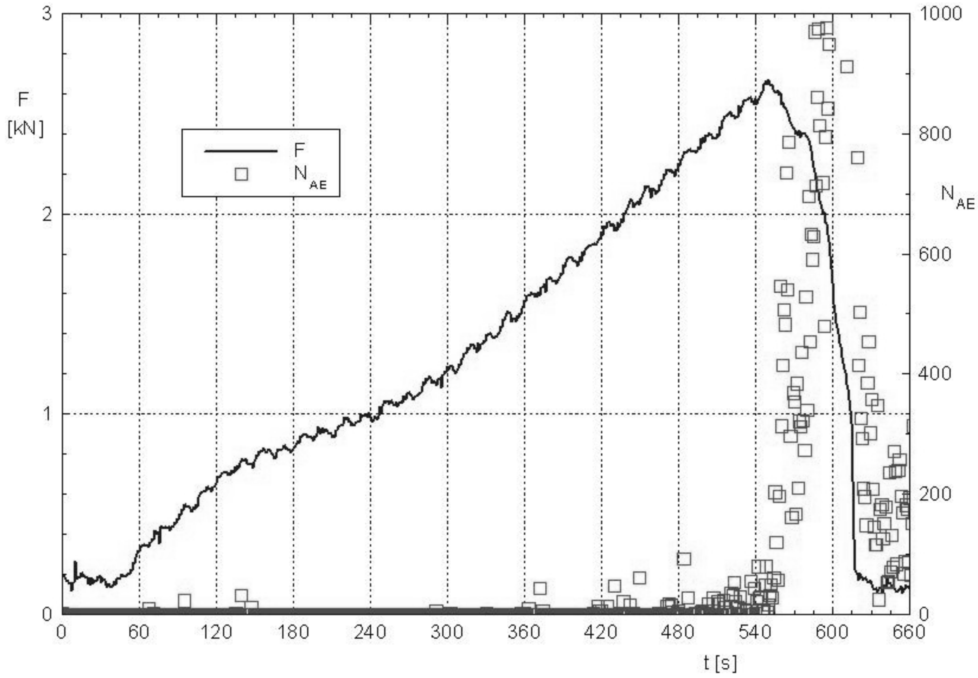

Figure 4 Time history of force, F, and acoustic emission counts, N_{AE}

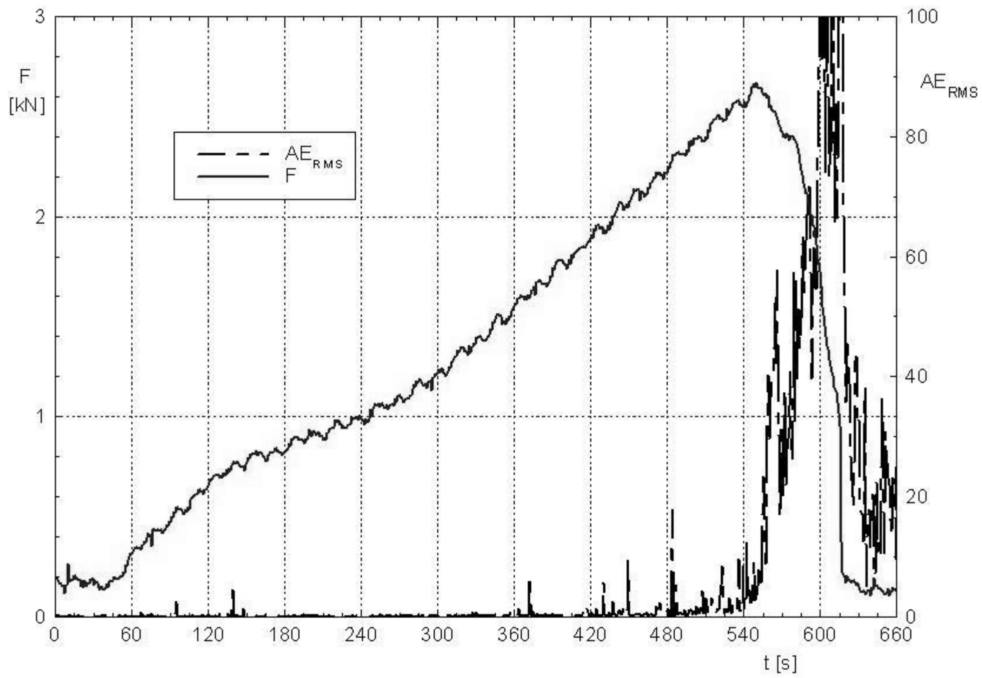

Figure 5 Time history of force, F, and acoustic emission RMS, AE_{RMS}

These forces were further used to calculation of corresponding values of initiation stress intensity factor, K_{Ic}^{ini}, and also unstable fracture toughness, K_{Ic}^{un}, using double-K fracture model. [8] Output data are summarized in the Tab. 1. Ratio between load at the beginning of stable crack propagation, F_{ini}, and maximum load, F_{max} (even and ratio $\frac{K_{Ic}^{ini}}{K_{Ic}^{un}}$) is showen Tab. 2.

F_{ini} (F_{max}) [N]	530	740	1600	(2700)
K_{Ic}^{ini} (K_{Ic}^{un}) [MPa·m$^{1/2}$]	0.0765	0.1068	0.2309	(0.5854)

Table 1 Output data of double-*K* fracture model

$\frac{F_{ini}}{F_{\max}}$ [-]	0.196	0.274	0.593
$\frac{K_{Ic}^{ini}}{K_{Ic}^{un}}$ [-]	0.131	0.182	0.394

Table 2 Ratio of load (forces), ratio between the levels of toughness

Based on our obtained outputs of double-*K* fracture model from three-point bending tests on plain concrete specimens introduced e.g. in [7,8], it can be estimated that load at the beginning of stable crack propagation is in this case probably 1.6 kN.

Acoustic emission energy of events (Fig. 6) at 1.6 kN is 68×10^{-12} V^2·s, respectively 153×10^{-9} V·s and at 2.7 kN is 108×10^{-12}.V^2·s, respectively 225×10^{-9} V·s. [6]

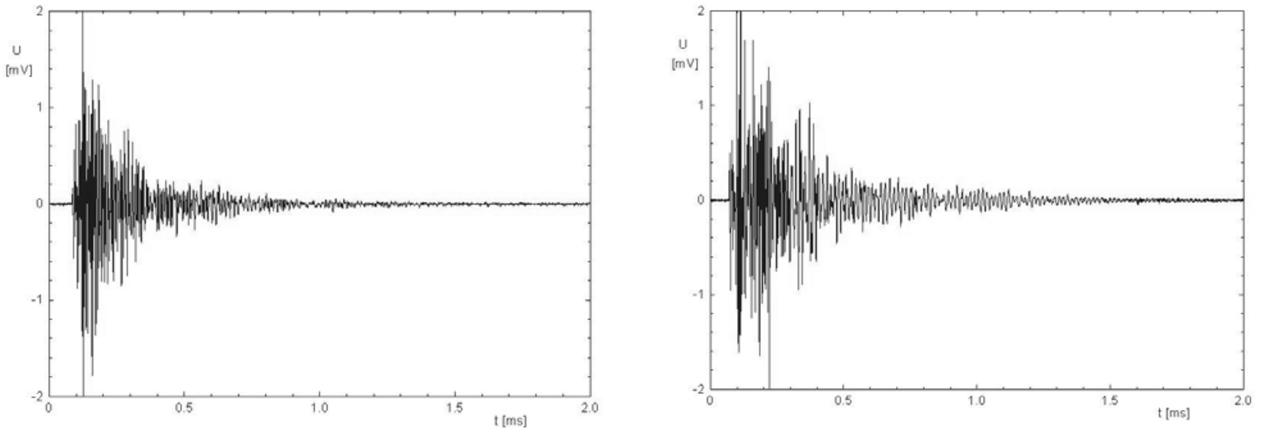

Figure 6 Acoustic emission events – at force 1.6 kN (left) and at 2.7 kN (right) after start loading

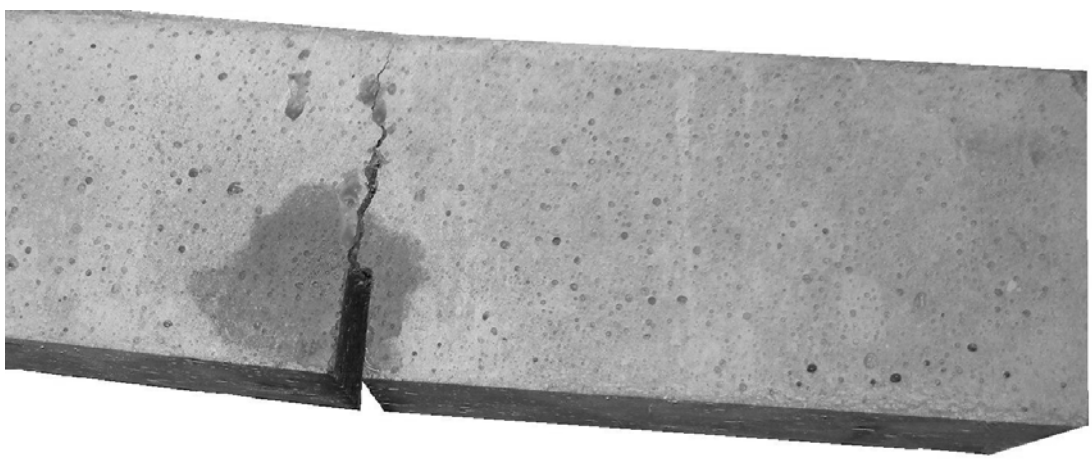

Figure 7 The specimen after three-point bending test

The experiment was stopped at the moment when the specimen was broken as it is shown in Fig. 7.

Conclusion

The acoustic emission method captures acoustic-emission parameters, including acoustic-emission counts, amplitude peak and energies. These parameters can be correlated with the defects formation and failures. The acoustic emission method was found to be an effective way of detecting fatigue and fracture behaviour of materials.

The acoustic emission results can be used as inputs to double-*K* fracture model, mainly in the case there are lacking records of *F–CMOD* diagram or *F–d* diagram form three-point bending test, which are usually used as inputs for this model. In this case, levels of loading F_{ini} and F_{max} were used as input values for double-*K* fracture model and values of initiation stress intensity factor K_{Ic}^{ini} and unstable fracture toughness K_{Ic}^{un} were calculated. Based on our up to know obtained results using double-*K* fracture model, from obtained ratio $\frac{K_{Ic}^{ini}}{K_{Ic}^{un}}$ it can be estimated that load at the beginning of stable crack propagation is in this case probably 1.6 kN.

Acknowledgement

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