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CRACK PROPAGATION IN CEMENTITIOUS MATERIALS BY ACOUSTIC EMISSION BASED ON FRACTURE MECHANICS

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ABSTRACT

Acoustic emission (AE) techniques are applied to clarifying fracture mechanics in cementitious materials. Crack traces due to mixed-mode cracking are numerically analyzed by applying the boundary element method (BEM). Here, in order to determine the critical stress intensity factor prior to nucleating the fracture process zone, AE rate process analysis is applied to the three-point bending tests of notched concrete beams. AE-SiGMA analysis is implemented to characterize kinematics of cracks, classifying crack types and determining crack orientations. Thus, mixed-mode crack propagation in cementitious materials is clarified by AE analysis based on fracture mechanics..

KEYWORDS

Acoustic emission (AE), Boundary element method (BEM), Cementitious materials, Rate process analysis, SiGMA Analysis

INTRODUCTION

The increase of aging structures and the disastrous damage due to earthquakes updatedly demand for clarifying the failure mechanisms of concrete structures. To this end, crack propagation in cementitious materials has been recently studied on the basis of fracture mechanics. Acoustic emission (AE) techniques have been extensively studied in concrete engineering, where it is known that one promising approach is the application of AE to fracture mechanics. Concerning the theoretical treatment, the generalized theory of AE was established on the basis of elastodynamics [1]. It is already clarified that AE waves are elastic waves due to dynamic crack motions in cementitious materials [2]. Based on these fundamental research, to classify crack types and determine crack orientation, the moment tensor analysis is implemented as the SiGMA (simplified Green's functions for the moment tensor analysis) code [3].

In the present paper, crack propagation in notched concrete beams is studied. The boundary element method (BEM) is applied to trace crack extension based on the linear elastic fracture mechanics (LEFM). The critical stress intensity factor K_{IC} is such a key parameter in the analysis that the value is estimated from AE rate process analysis [4]. Then, crack kinematics is clarified by applying the SiGMA analysis and compared with results of the BEM analysis.

THEORETICAL BACKGROUND

Rate Process Analysis

When concrete contains a number of critical microcracks, active AE occurrence is expected under compression due to crack propagation from the microcracks. In contrast, AE activity in sound concrete is known to be stable and low prior to final failure. Thus, to formulate AE activity under loading, the rate process theory was introduced [4]. Probability function f(V) of AE occurrence from stress level V(%) to V+dV (%) is formulated,

$$dN/N = f(V)\, dV. \qquad (1)$$

Assuming a hyperbolic function of the probability,

$$f(V) = a/V + b. \qquad (2)$$

.Eventually, a relationship between the number of total AE events N and stress level V(%) is derived as,

$$N = C\, V^{a} \exp(bV), \qquad (3)$$

where a and b are empirical coefficients and C is the integration constant. Then, a tangential equation is derived at the maximum stress level V = 100%, and an intersection with the stress level is determined as V',

$$V' = 1 - 1/(a + b) \qquad (4)$$

This stress level could correspond to initiation of crack propagation prior to nucleating the fracture process zone. Consequently, the load P' to determine the critical stress intensity factor K_{IC} is determined from the ultimate load P_{max} times V' ($P' = P_{max} \times V'$). As a result, K_{IC} is determined from the load level right before developing the fracture process zone in cementitious materials, satisfying the condition of small-scale yielding.

BEM Analysis

Elastic solutions of displacement **u**(**x**) are mathematically represented as,

$$C\, u_k(\mathbf{x}) = \int_S [G_{ki}(\mathbf{x},\mathbf{y}) t_i(\mathbf{y}) - T_{ki}(\mathbf{x},\mathbf{y}) u_i(\mathbf{y})] dS, \qquad (5)$$

where **u**(**x**) and **u**(**y**) are displacements, and **t**(**y**) are tractions. $G_{ik}(\mathbf{x},\mathbf{y})$ are Green's functions and $T_{ik}(\mathbf{x},\mathbf{y})$ are the associated tractions with Green's functions,

$$T_{ik}(\mathbf{x},\mathbf{y}) = G_{ip,q}(\mathbf{x},\mathbf{y})\, C_{pqjk} n_j. \qquad (6)$$

Here C_{pqji} are the elastic constants, and $G_{ip,q}(\mathbf{x},\mathbf{y})$ are the spatial derivatives of Green's functions. **n** is the normal vector to the boundary surface S. In BEM, eq. 5 is directly digitized and numerically solved, where C=1/2 and all points **x** and **y** are prescribed on the boundary S.

According to LEFM, the angle of crack extension θ is obtained from the maximum circumferential stress [5],

$$K_I \sin\theta + K_{II}(3\cos\theta - 1) = 0. \qquad (7)$$

Here K_I and K_{II} are the stress intensity factors of mode I and mode II, which can be computed from the displacements on the crack-tip elements in BEM. Introducing the critical stress intensity factor K_{IC}, the initiation of crack extension is governed by,

$$\cos\theta/2[K_I\cos^2\theta/2 - 3/2(K_{II}\sin\theta) = K_{IC}. \qquad (8)$$

Implementing the above criterion of eqs. 7 and 8 into BEM, the automatic analysis of crack propagation in an arbitrary orientation has been developed by employing the two-domain BEM [6].

SiGMA Analysis

In order to model a crack as an AE source, the boundary surface S in eq. 5 is replaced by crack surface F. Taking into account the discontinuity, $\mathbf{b}(\mathbf{y},t)$, of displacements on the crack surface, eqs. 5 and 6 are reformulated as,

$$u_k(\mathbf{x},t) = \int_F T_{ki}(\mathbf{x},\mathbf{y},t)*b_i(\mathbf{y},t)\, dF = G_{kp,q}(\mathbf{x},\mathbf{y},t)*S(t)\, C_{pqij}\, n_j l_i \Delta V, \qquad (9)$$

where $\mathbf{l}$ is the unit direction vector and S(t) is the source-time function of crack motion. ΔV is the crack volume. Introducing moment tensor $M_{pq} = C_{pqkl} l_k n_l \Delta V$, eq. 9 is simplified,

$$u_k(\mathbf{x},t) = G_{kp,q}(\mathbf{x},\mathbf{y},t)\, M_{pq}*S(t). \qquad (10)$$

Based on the far-filed term in eq. 10, a simplified procedure suitable for a PC-based processor was developed. The procedure is implemented as a SiGMA (Simplified Green's functions for Moment tensor Analysis) code [3]. Since the moment tensor is symmetric and composed of six independent unknowns m_{pq}, multi-channel observation of the first motions at more than six channels is necessary and sufficient.

From AE waveform, the arrival time and the amplitude of the first motion are determined. In the source location procedure, location $\mathbf{y}$ is determined from the arrival time differences. From the amplitudes of the first motions at more than 6 channels, the components of the moment tensor are solved. The classification of a crack is performed by the eigenvalue analysis of the moment tensor. The eigenvalues of the moment tensor for a general case could be decomposed as X, Y, and Z which denote the shear ratio, the deviatoric tensile ratio, and the isotropic tensile ratio, respectively. AE sources of which the shear ratios are less than 40% are classified into tensile cracks. The sources of X > 60% are classified into shear cracks. In between 40% and 60%, cracks are referred to as mixed mode. In the eigenvalue analysis, three eigenvectors are also determined, and then the vectors **l** and **n** which are interchangeable are recovered.

EXPERIMENT

Three-point bending tests of notched concrete beams were conducted. To apply AE rate process analysis and SiGMA analysis, notched beams of dimensions 10 cm x 10 cm x 40 cm were made of concrete. By sawing the specimens, a notch of either 5 cm depth or 7 cm depth was made with 1 mm thickness. The compressive strength of concrete was 37.9 MPa, the tensile strength was 3.03 MPa and Young's modulus was 29.7 GPa after 28 day moisture-cure. The load was applied monotonously up to the final failure, monitoring AE events. AE sensor was of 1 MHz resonance. Total amplification was 6o dB and the frequency range was 10 kHz to 1 MHz. A sketch of the specimen and AE sensor array is given in Figure 1. AE rate process analysis was conducted in center-notched specimens (the notch of solid line) by employing one-channel system, while six-channel system was employed to apply the SiGMA procedure to off-center notched specimens (the notch of broken line).

RESULTS AND DISCUSSION

The Critical Stress Intensity Factor

AE events were observed in the three-point bending tests of the center-notched specimens. Results are given in Figure 2. AE activity is approximated by eq. 3 and then the stress level V' is determined. As a result, the critical stress intensity factors were computed as 0.827 MPa $m^{1/2}$ for 5 cm notch and 0.723 MPa $m^{1/2}$ for 7cm notch. These values were checked by Barenblatt's criterion,

$$d > (K_{IC}/\sigma_t)^2, \qquad (11)$$

where d is the notch depth and σ_t is the tensile strength. It is obtained that d > 4.96 cm for 5 cm notch and d > 3.06 cm for 7 cm notch. The criterion is just satisfied in the case of 5 cm notch and completely for 7 cm notch.

To investigate an applicability of these values, BEM analysis was conducted for the center-notched specimens. Results are shown in Figure 3. In the case of 5 cm notch, an analytical result on the load versus crack-mouth opening displacement (CMOD) relation becomes unstable after reaching the peak value, while the relation of 7 cm notch is stable and in reasonable agreement with experimental results. Consequently, The value K_{IC} = 0.723 MPa $m^{1/2}$ is selected for the analysis of the off-center notch.

Crack Traces

Crack propagation was observed in the three-point bending of the off-center notched specimens. Three traces observed are given in Figure 4. BEM analysis was conducted to simulate the crack propagation. As can be seen, remarkable agreement with experimental results is observed. Thus, an applicability of eqs. 7 and 8 to analyze the crack trace of mixed-mode propagation. in concrete is confirmed.

Crack Kinematics

Results of SiGMA analysis for the off-center notched specimen is shown in Figure 5. Cracks identified are plotted at their locations. Those of tensile cracks are indicated by arrow symbol of which directions are identical to opening directions, while those of mixed-mode and shear are represented by cross symbol of which two directions correspond to the motion of crack and the normal vector to the crack surface.

Surface cracks observed at both the top and the bottom surfaces are indicated by broken lines. It is observed that both types of cracks are generated and fully mixed at their locations. Still, it seems that the shear cracks are observed as close as the final crack surface, indicating that the shear cracks are mostly generated along the existing crack surfaces. To compare with the analytical results by BEM, the ratios of the stress intensity factors K_I/K_{II} in the analysis are plotted against the crack extension length as given in Figure 6. It is clearly observed that the ratios are mostly larger than 1.0, implying that the dominant motions are of the opening mode. After propagating around 3.5 cm, the ratio abruptly decreases smaller than 1.0, indicating the presence of the dominant shear motions. Thus, the mixed nature of crack propagation in concrete is clarified, although the dominant mechanisms are of mode I.

CONCLUSION

Crack propagation in notched concrete beams is studied numerically and experimentally. Resulst are concluded, as follows:
(1) In the case of 7 cm notch, K_{IC} value estimated is fully satisfied with Barenblatt's criterion. The analytical result on the load-CMOD relation by BEM is stable and in reasonable agreement with experimental results. The feasibility of the procedure to estimate K_{IC} in cementitious materials is demonstrated.
(2) Crack traces observed in the off-center notched specimens are simulated by BEM. Remarkable agreement with experimental results on crack surfaces is observed. The applicability of LEFM to analyzing the mixed-mode crack propagation is confirmed.
(3) From SiGMA analysis, it is observed that both types of cracks are fully mixed during crack extension in the off-center notched beam. The ratios of the stress intensity factors K_I/K_{II} are studied brom the results of BEM analysis. It is found that cracking mechanisms are mostly of mode I, although there is a stage where mode II is dominant.

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Figure 1: Experimental set-up and AE sensor array for an off-center notched specimen.

Figure 2: Results of AE rate process analysis in the three-point loading tests.

Figure 3: Results of load-CMOD curves and BEM analysis.

Figure 4: Crack traces.

Figure 5: Results of SiGMA analysis.

Figure 6: Ratio of the stress intensity factors K_I/K_{II} vs. crack length.