Mix-Mode Crack Propagation in Concrete analyzed by Boundary Element Method

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1. Introduction

Quantitative information on cracking mechanisms can be obtained from the linear elastic fracture mechanics (LEFM). The maximum circumferential stress criterion based on LEFM was successfully applied to trace the crack extension of mixed-mode cracking[1)]. By employing the two-domain Boundary Element Method (BEM), crack orientations were evaluated from the stress intensity factors of mode I and mode II. Therefore, shift of dominant failure mode from mode I to mode II is studied in the case of simulated corrosion cracking.

2. Experiment

One day after concrete was cast into steel mold, specimens were removed from the molds and moisture cured in water for 28 days in the standard room (20^{o}C). The mixture proportion of concrete was made up as water(W): cement(C): sand(S): gravel(G) = 0.5:1.0:2.41:2.95 by weight. The maximum size of aggregate was 20mm. Slump value and air content were 8.0 cm and 5.0%, respectively. By employing a slab specimen (dimension: 25cmX25cmX10cm), experiments were carried out for simulation of corrosion cracking. Two cases of 3cm and 8cm cover thickness as were studied. Cylindrical specimens (dimension: 10cm diameter X 20cm height) were tested for mechanical properties of concrete.

To simulate corrosion cracking of mixed mode, an expansion test was conducted. Cracks due to corrosion of reinforcements are generated in the long process and very difficult to examine in the short time by an experiment. Thus, hydrostatic radial pressure is introduced by employing expansive agent. In Figs. 1 and 2, two circles of 3.0cm diameter represent the locations of the reinforcement where the expansion pressure was applied by dolomite paste. Crack patterns due to the expansion are shown in the figures. The crack traces are denoted by mark A,B, and C for 3cm cover thickness in Fig.1 and denoted by mark D,E, and F for 8cm cover thickness in Fig.2. These crack traces are analyzed by BEM simulation.

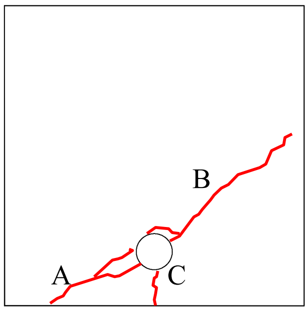

Fig.1 Corrosion cracking by expansive agent (3cm cover thickness)

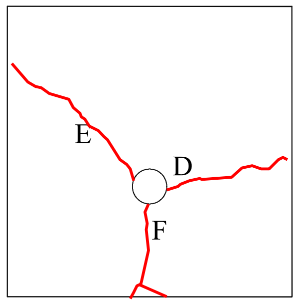

Fig.2 Corrosion cracking by expansive agent (8cm cover thickness)

3. Crack Analysis By BEM

An analytical model for the analysis of crack propagation is shown in Fig.3. At each step of the analysis, the stress intensity factor at the crack tip was computed from the displacement on the crack-tip element. When a crack propagates, the node at the crack tip is separated into two nodes, creating a new stress-free crack boundary in the direction θ as shown in Fig.4. The direction of the maximum tangential stress θ is determined by Erdogan-Sih criterion[2)]:

$$K_I \sin\theta + K_{II}(3\cos\theta - 1) = 0 \qquad (1) \qquad \text{and} \qquad \cos\frac{\theta}{2}\left[K_I \cos^2\left(\frac{\theta}{2}\right) - \frac{3}{2}K_{II}\sin\theta\right] = K_{IC} \qquad (2)$$

where K_I and K_{II} are the stress intensity factors of mode I and mode II, respectively. K_{IC} is the critical stress intensity factor determined from AE observation[3)]. Using the value K_{IC}=0.723MPa m$^{1/2}$ for an input data, crack propagations are analyzed by BEM.

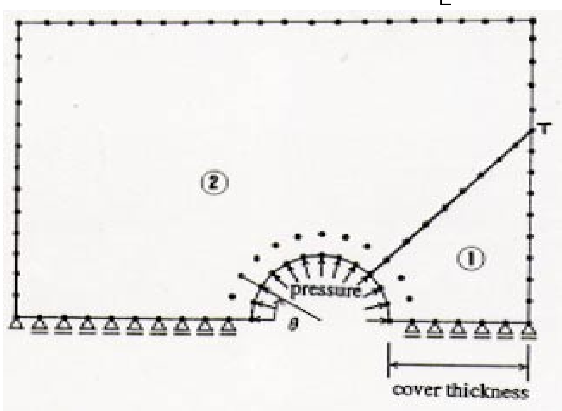

Fig. 3 Two-domain BEM model

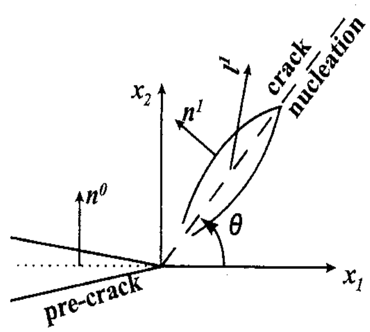

Fig.4 Configuration of crack extension

Keywords: mixed-mode cracking; crack extension; stress intensity factors; corrosion cracking; BEM
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4. Results and Discussion

The experimental results of crack propagation due to expansive agent were compared with the analytical results. In each crack trace, is separately analyzed by the two-domain BEM model. Results are given in Figs. 5 and 6. The simulated crack traces show remarkable agreement with all the actual crack traces in Figs. 1 and 2. Ratios of stress intensity factors of mode I to mode II are plotted with the increment of crack extension, as shown in Figs.7 and 8. It is observed that for crack traces A and C in 3cm cover thickness, the ratios of stress intensity factors (K_I/K_{II}) are greater than 1.0 except crack trace B. This indicates that the crack starts with almost mode-I fracture. This result reveals that the mode-I fracture dominates than mode-II fracture for crack traces A and C. In crack trace B, the ratios (K_I/K_{II}) almost keep lower than 1.0 indicating the mode II is dominant. The larger ratios are observed in 8cm cover thickness for crack traces E and F. This implies that the dominant fracture is of tensile mode except crack trace D. Thus, it is found that these crack traces are generated due to different cracking mechanisms due to corrosion.

5. Conclusion

As a numerical technique, two-domain BEM is very promising for analyzing the mixed-mode crack extension based on the maximum circumferential stress criterion. The method is readily applicable and allows simple automatic remeshing to model crack extension. Obtained results are summarized: (1) Crack propagations are simulated by the two-domain BEM analysis, applying K_{IC} value determined. (2) Cracks of mixed-mode propagate due to the expansion of corrosive products, which are simulated by BEM with reasonable accuracy. (3) Crack initiation seems to be mostly of the mode-I type, resulting in the interaction with the mode II as the crack propagates.

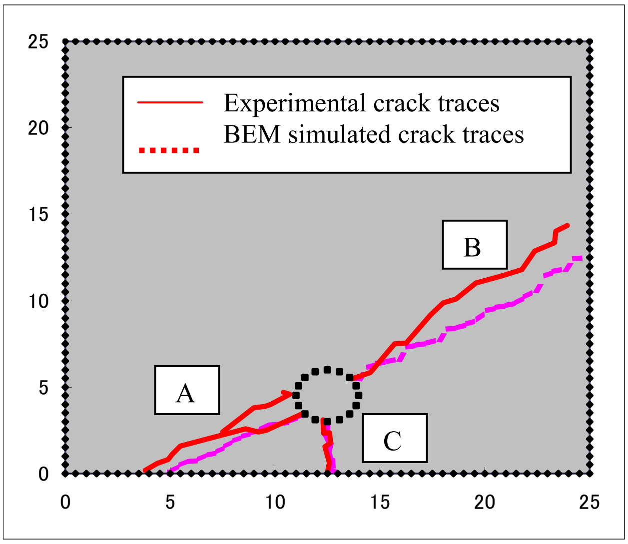

Fig.5 Experimental crack traces superimposed on BEM simulated crack traces (crack traces A, B, and C)

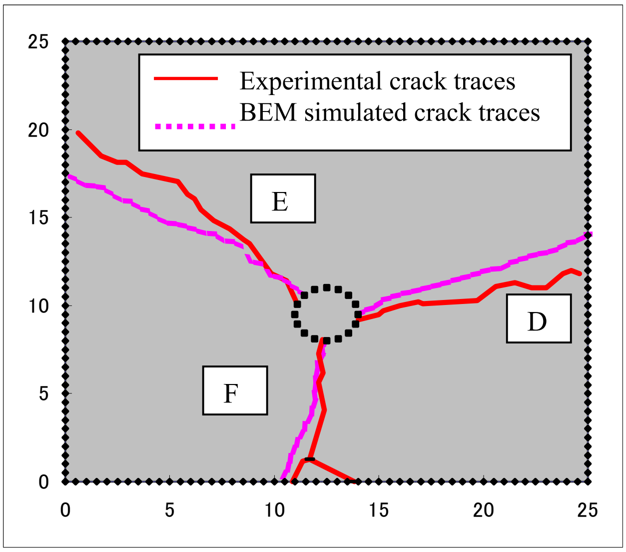

Fig.6 Experimental crack traces superimposed on BEM simulated crack traces (crack traces D,E, and F)

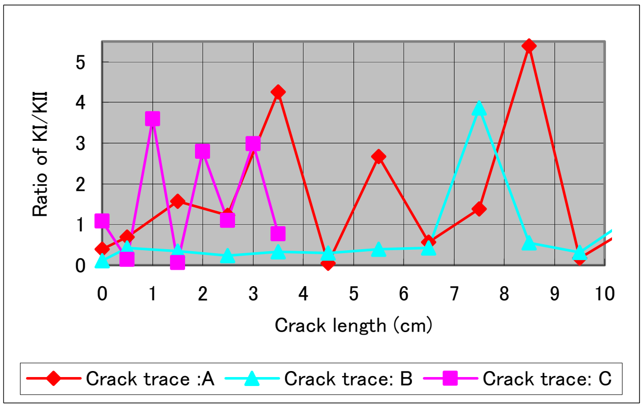

Fig.7 Ratios of stress intensity factors (K_I/K_{II}) vs. crack extension for crack trace: A, B, and C

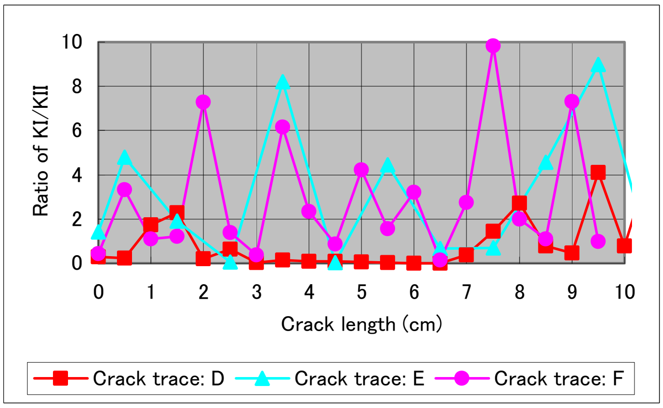

Fig.8 Ratios of stress intensity factors (K_I/K_{II}) vs. crack extension for crack trace: D, E, and F

References

1. Chahrour, A.H., Fukuchi, S., Ohtsu, M. and Tomoda, Y., *BEM Analysis of Mixed-Mode Crack Propagation in Center-Notched Concrete Beams*, Transactions of JCI, Vol.15, pp. 201-208,1993.12
2. Erdogan, F. and Sih, G.C., *On the Crack Extension in Plates under Plane Loading and Transverse Shear.* J. Basic Eng., No.12, pp.519-527, 1963.12
3. Farid Uddin A.K.M., *Fracture Toughness of Concrete and Analysis of Crack Propagation Method*. Master Thesis, Graduate School of Science and Technology, Kumamoto University; pp:19, 2001.2