Numerical Investigation of Nonlinear Concrete Fracture Behavior using Cohesive Zone Modeling

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1. Introduction

Concrete has been widely utilized as a major construction material for civil infrastructures due to its high compressive strength, low cost, shape flexibility, etc. Additionally, concrete possesses high radiation shielding property and therefore reinforced concrete structure is mainly used for containment buildings of nuclear power plants preventing radioactive material leakage to the environment. Compared to the high compressive strength, however, concrete has relatively low tensile strength. Tensile cracking of concrete can adversely affect durability of infrastructures associated with steel corrosion and concrete permeability. In this study, a computational framework is presented to investigate nonlinear fracture behavior of concrete using cohesive zone modeling. To represent an arbitrary crack path in the finite element domain, an adaptive element splitting scheme is utilized in conjunction with the virtual grid-based stress recovery and the domain integral method [1, 4]. Then, mixed-mode concrete fracture examples are illustrated to demonstrate the accuracy and robustness of the proposed method.

2. Crack Propagation Modeling

In this section, a computational methodology is presented to illustrate nonlinear fracture behavior of concrete. First, the weak form of the governing equation for quasi-static cohesive fracture is explained. Next, the element splitting procedure is illustrated. Then, the crack growth criterion is described based on the virtual grid-based stress recovery and the domain integral method.

2.1 Weak Form of the Governing Equation

For simulation of concrete cohesive fracture, the governing equation is based on the principle of virtual work. The internal virtual work within a domain (Ω_0) is equal to the sum of the virtual work done by the external traction ($\mathbf{T}^{\text{ext}}$) and the cohesive traction ($\mathbf{T}^{\text{coh}}$), given as

$$\int_{\Omega_0} \delta\mathbf{E} : \mathbf{S}\, d\Omega_0 = \int_{\Gamma_0} \delta\mathbf{u} \cdot \mathbf{T}^{\text{ext}}\, d\Gamma_0 + \int_{\Gamma_{\text{coh}}} \delta\boldsymbol{\Delta} \cdot \mathbf{T}^{\text{coh}}\, d\Gamma_0 \qquad (1)$$

where $\delta\mathbf{E}$ is the virtual Lagrangian strain, $\mathbf{S}$ is the second Piola-Kirchoff stress, $\delta\mathbf{u}$ is the virtual displacement, and $\delta\boldsymbol{\Delta}$ is the virtual separation. Additionally, Γ_0 is the boundary surface, and Γ_{coh} is the fracture surface. Then, based on the Galerkin approximation, a system of nonlinear equations is obtained from the weak form, i.e., $\mathbf{f}^{\text{int}} = \mathbf{f}^{\text{ext}} + \mathbf{f}^{\text{coh}}$, where $\mathbf{f}^{\text{int}}$, $\mathbf{f}^{\text{ext}}$, and $\mathbf{f}^{\text{coh}}$ are the internal, external, and cohesive force vectors, respectively.

2.2 Adaptive Element Splitting Scheme

To describe an arbitrary crack path in the finite element mesh, the element splitting scheme is utilized [1]. Once a crack propagation direction is evaluated at a crack tip, one splits a continuum triangular element along the crack propagation direction, as shown in Fig. 1. Then, a new (crack-tip) node is created on an edge of the element. Next, an element on the opposite side of the edge is split to keep the topological consistency of the mesh. Finally, a new crack surface is represented by inserting a cohesive surface element along a newly created edge which is identical to the crack propagation direction.

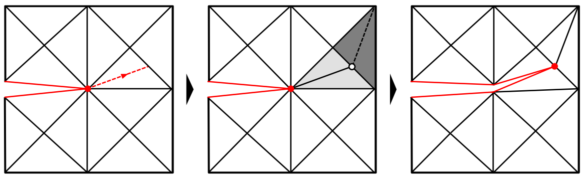

Fig. 1. Arbitrary crack path representation using the element splitting scheme.

2.3 Crack Growth Criterion

For the evaluation of the crack propagation direction, the maximum strain energy release rate criterion is employed. In this criterion, a crack propagates along the direction where the strain energy release rate is maximized. To calculate a strain energy release rate, the *J*-integral is utilized in conjunction with the domain integral method, which is given as

$$J = \int_A \left(\sigma_{ij}\frac{\partial u_j}{\partial x_k} - W\delta_{ki}\right)\frac{\partial q_k}{\partial x_i}dA - \int_{C^+ + C^-} t_i \frac{\partial u_i}{\partial x_k} q_k dC \qquad (2)$$

where σ_{ij}, t_i, and u_i are the components of the stress, traction, and displacement, respectively. x_k represents the local crack coordinate system. Additionally, W is the strain energy, δ_{ij} is the Kronecker delta, and q is an arbitrary smooth function, e.g., a plateau function. Because the *J*-integral is evaluated based on the displacement and stress fields around the crack tip region, one should obtain those fields, precisely. To calculate the accurate stress field around a crack-tip region, the virtual grid-based stress recovery (VGSR) technique is employed, which reduces errors associated with the numerical differentiation on low-quality meshes generated during element split [2]. A virtual grid is generated where one wants to determine a stress field, and then the domain integral is performed in the virtual grid instead of the finite element mesh (see Fig. 2.). Note that the location and shape of the virtual grid are determined according to a crack trajectory and a crack tip location.

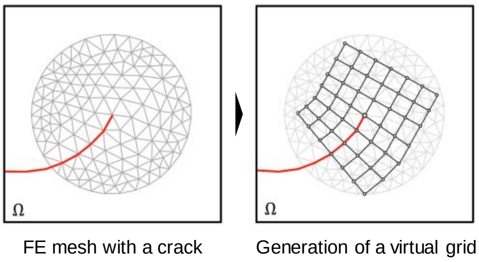

Fig. 2. Virtual grid generation around a crack tip.

3. Mixed-mode Fracture Example

To validate the proposed computational framework, two mixed-mode fracture examples of plain concrete are illustrated, i.e., a four-point shear test and a double-edge-notched specimen test [3,5]. For the cohesive constitutive model of plain concrete, the bilinear softening curve is employed.

3.1 Four-point shear test

The test configuration of a four-point shear test is illustrated in Fig. 3. The material properties of concrete specimen are obtained from the experiment data, i.e., the elastic modulus is 30 GPa, and Poisson's ratio is 0.2.

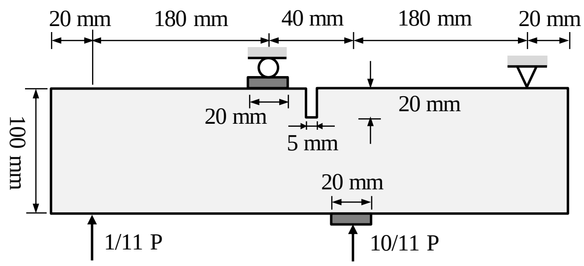

Fig. 3. Test configuration of the four-point shear test.

A computational result of the crack path is plotted in Fig. 4. The crack initially propagates from the bottom-right corner of the initial notch with an angle of 42˚. Then, the crack direction gradually changes along the vertical direction. The predicted crack path is well matched with the experimental results. In addition, the load-displacement relationship is computed and compared with the experimental one. As shown in Fig. 5, the proposed computational method well captures the experimental result.

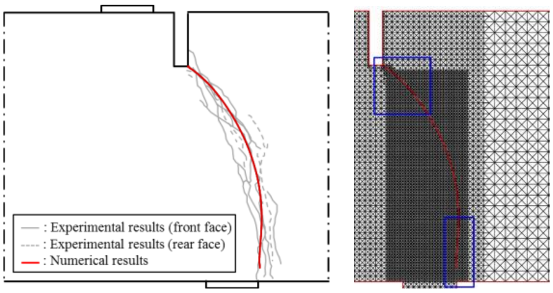

Fig. 4. Computed crack path and its comparison with the experimental result.

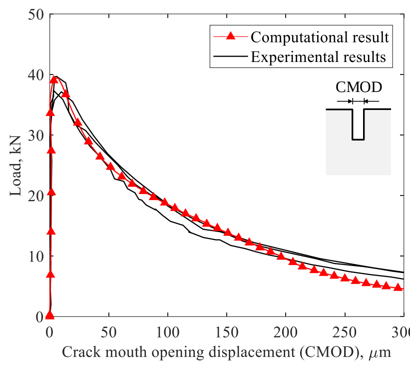

Fig. 5. Comparison between the experimental and computational results for the load-crack mouth opening displacement (CMOD) relationship.

3.2 Double-edge-notched specimen test

For the second mixed-mode fracture example, a double-edge-notched specimen test is selected, as shown in Figure 6. The elastic modulus and Poisson's ratio of the concrete specimen are 32.8 GPa and 0.2, respectively. The specimen has two initial notches of 25 mm on the middle of left and right edges. A horizontal force of 10 kN is applied on the upper-left edge and then, vertical displacement is applied along the top surface.

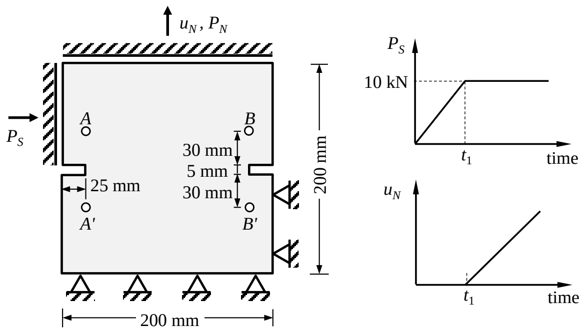

Fig. 6. Test configuration of the double-edge-notched specimen test.

A computed crack path is illustrated and compared with the experimental one in Figure 7. From two initial notches, cracks propagate with an initial angle of 60˚, and then the direction of crack gradually changes. Computational results show that the predicted crack path is well matched with the experimental one. Also, the computed load-displacement relationship is well matched with the experimental result. Note that the proposed method shows better accuracy for the global behavior than other methods (e.g., XFEM and micro-plane model), as shown in Figure 8.

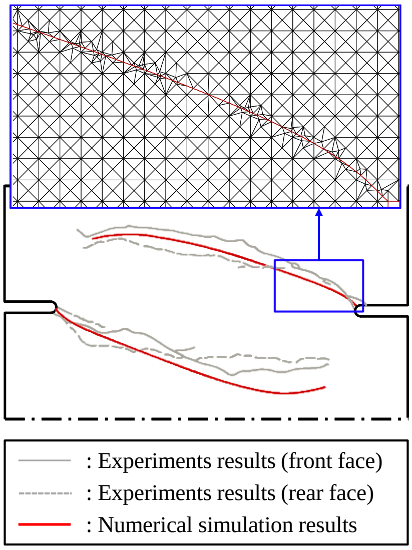

Fig. 7. Comparison between the computed crack path and the experimental result.

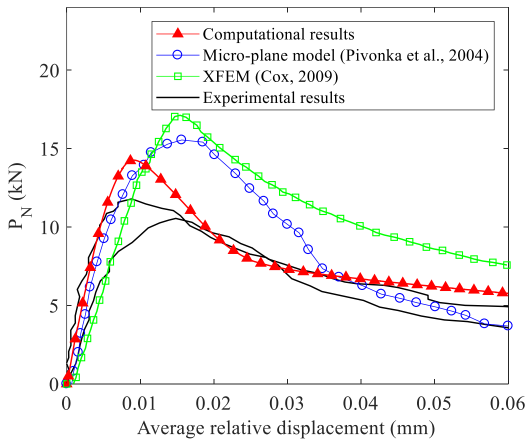

Fig. 8. Comparison between the computed and experimental load versus displacement relationships.

4. Conclusions

To investigate the mixed-mode fracture of concrete, a cohesive zone-based element splitting scheme is utilized in conjunction with VGSR and the domain integral method. By adaptively splitting continuum elements along the evaluated crack path direction, accurate and smooth crack path is captured. VGSR with the *J*-integral method provides accurate stress field around a crack tip region, and the crack propagation direction. Two mixed-mode concrete fracture examples are solved using the proposed computational framework, and the computed results are well matched with the experimental ones.

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