Numerical Study on Nonlinear Fracture Behavior of Concrete Hollow Cylinder under Tensile Loading

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1. Introduction

Concrete is one of the most widely utilized materials for the construction of civil infrastructures due to its high compressive strength, flexibility in size and shape, durability, etc. Also, reinforced concrete is mainly employed in the construction of containment buildings of nuclear power plants, which represents the final barrier of radioactive materials in a severe accident. However, since concrete has low tensile strength, concrete is vulnerable to tensile loads, resulting in tensile cracking that affects the safety of concrete structures. In this study, to accurately predict such nonlinear fracture behavior of concrete, a computational framework is presented based on the cohesive surface element approach. For the representation of an arbitrary crack path in a finite element domain, continuum elements adaptively split along the calculated crack path, and then a cohesive surface element is inserted along the crack path [1, 2]. To predict the direction of crack path, the maximum strain energy release rate criterion is utilized. Then, a concrete hollow cylinder test is investigated to validate the accuracy and robustness of the proposed methodology.

2. Crack Propagation Modeling

In this section, a computational methodology is presented to illustrate nonlinear fracture behavior of concrete. First, the adaptive element splitting scheme is illustrated to represent an arbitrary crack path in a finite element domain. Then, the cohesive traction-separation relationship is described, which accounts for the tensile fracture behavior of concrete. Finally, the crack growth criterion is explained.

2.1 Adaptive Element Splitting Scheme

To describe an arbitrary crack path in the finite element mesh, the adaptive element splitting scheme is employed [1,2]. When a crack propagation direction is calculated based on the crack growth criterion, a continuum triangular element split along the crack propagation direction, as shown in Fig. 1. Then, a new crack-tip node is generated on an edge of the element. Next, another adjacent element of the edge is divided to maintain the topological consistency of the mesh. Finally, one inserts a cohesive surface element along a newly generated edge to represent a new crack surface.

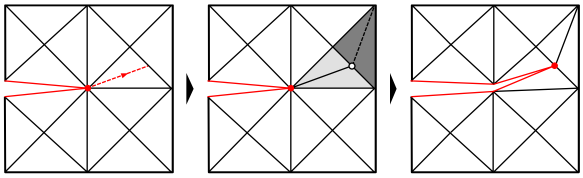

Fig. 1. Arbitrary crack path representation using the element splitting scheme.

2.2 Cohesive Traction-separation Relationship for Concrete

For the cohesive traction-separation relationship of concrete, a bilinear softening model is employed, which has been widely utilized to describe the tensile fracture behavior of plain concrete [3,4]. The bilinear softening model is generally defined using four fracture parameters, i.e., cohesive strength (σ_{max}), total fracture energy (G_F), initial fracture energy (G_{if}), and kink point ratio(ψ), as shown in Fig. 2. For the cohesive strength, the indirect tensile strength of concrete is utilized while the total fracture energy is estimated using the work-of-fracture method [5].

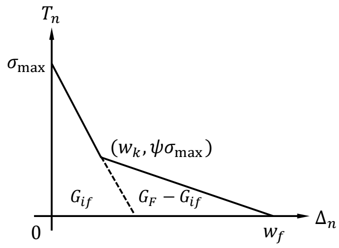

Fig. 2. Bilinear softening model for plain concrete fracture.

2.3 Crack Growth Criterion

For the evaluation of the crack propagation direction, the maximum strain energy release rate criterion (MSERR) is utilized. Based on MSERR, a crack propagates to 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

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

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. In this study, a plateau function is utilized for the q function which is zero on the boundary and unity at the crack tip. Because the *J*-integral is evaluated based on the displacement and its gradient fields around the crack tip region, one should obtain those fields, accurately. To evaluate the accurate stress field around a crack-tip region, the virtual grid-based stress recovery (VGSR) technique is employed, which decreases errors associated with the numerical differentiation on low-quality meshes generated during element split [6]. A virtual grid is generated around a crack-tip region, and then the domain integral is performed in the virtual grid instead of the finite element mesh (see Fig. 3). Note that the location and shape of the virtual grid are determined according to a crack trajectory and a crack tip location. Then, when a tensile stress along the evaluated crack path direction is greater than the cohesive strength, one assumes that the crack propagates along the calculated direction.

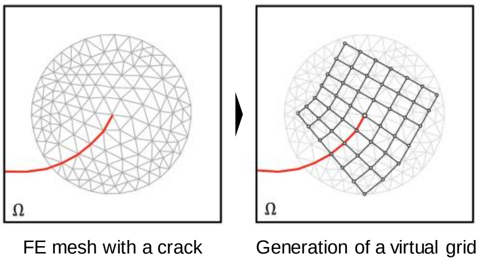

Fig. 3. Virtual grid generation around a crack tip.

3. Concrete Hollow Cylinder Test under Tensile Loading

To validate the proposed computational framework, concrete hollow cylinder test is illustrated under tensile loading [7], as shown in Fig. 4. A specimen has a diameter of 356 mm with a thickness of 77 mm. The 28-days concrete strength of the specimen is 28.1 MPa. Then, the specimen is loaded in direct tension at a rate of 0.005 mm/s until cracking occurred.

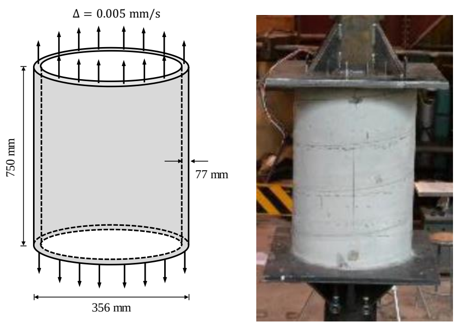

Fig. 4. Geometry and boundary conditions of the concrete hollow cylinder test.

For the numerical simulation, elastic modulus and Poisson's ratio of concrete are selected as 25.8 GPa and 0.2, respectively. For the fracture parameters of concrete, G_F is 100 N/m and σ_{max} is 3 MPa. Then, the ratio of G_F to G_{if} is assumed as 2.5, while ψ is selected as 0.33 for the bilinear softening model. To model the concrete cylinder specimen in 2D, one assumes the specimen as two-dimensional rectangular domain as shown in Fig. 5(a). The length of the domain is 1120 mm with a cross section of 750 × 77 mm. A vertical displacement is applied along the top surface of the domain. For the mesh discretization, a linear triangular mesh is employed. The number of elements and nodes are 99,752 and 50,200, respectively. The average element size of the mesh is 3 mm. Note that 30% of variation is applied on the elastic modulus of the concrete to provide the randomness on the crack initiation [see Fig. 5(b)].

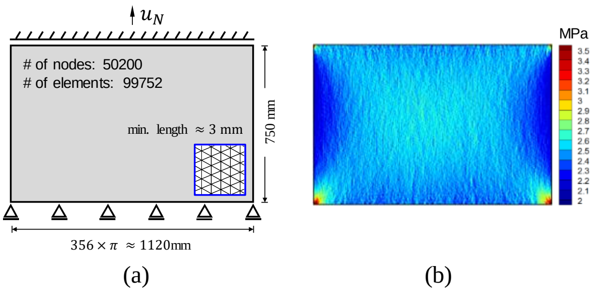

Fig. 5. (a) 2D numerical modeling of the concrete cylinder test and (b) principal stress contour according to the variation of elastic modulus.

A computational result of the crack path is plotted in Fig. 6. Cracks are initially generated in the middle of the domain and then propagate horizontally because of the vertical tensile loading. Compared to the experimental results, the computed crack patterns are well matched with the experimental one.

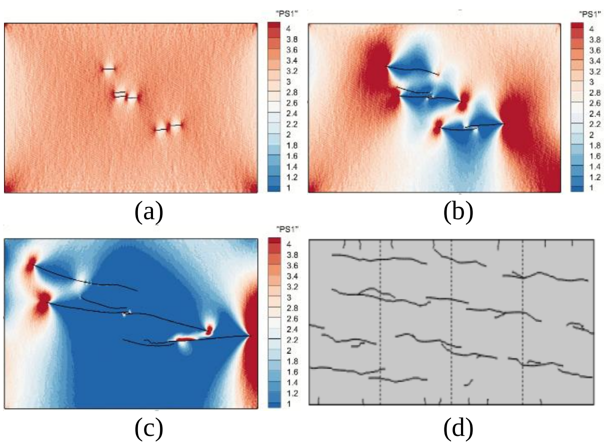

Fig. 6. Computed crack patterns at (a) $u = 0.05$ mm, (b) $u = 0.1$ mm, (c) $u = 0.3$ mm, and (d) experimental results.

4. Conclusions

To investigate the concrete fracture behavior under tensile loading, 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 propagation direction, accurate and smooth crack pattern is represented. VGSR with the *J*-integral method provides accurate stress field around a crack tip region, and the crack propagation direction. Concrete hollow cylinder test under tensile loading is numerically investigated using the proposed computational framework, and the computed crack patterns are well matched with the experimental ones.

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