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Numerical Simulation of Two- and Three-dimensional Nonlinear Crack Propagation in Concrete of Containment Building using Cohesive Zone Modeling

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1. Introduction

Concrete has been considered as one of the major construction materials for civil infrastructure due to its durability, affordability, shape flexibility, and more. Concrete is also used as the primary construction material for containment building of nuclear power plants due to its radiation shielding ability. Compared to its high compressive strength, concrete is generally vulnerable to tensile loading, which can lead to tensile cracking that compromises the safety of concrete structures. For example, in containment buildings, concrete cracking can result in the leakage of radioactive materials into the environment. In this study, we present a computation framework for predicting the nonlinear crack propagation behavior of concrete based on the cohesive zone modeling. To represent arbitrary crack propagation in the finite element mesh, continuum elements are adaptively split along the crack propagation direction, and cohesive surface elements are inserted along the boundaries of the split elements. Here, the surface elements represent discontinuities within the finite element mesh. By solving benchmark examples, the accuracy and robustness of the proposed method are verified, and its applicability to assessing crack propagation behavior in containment walls is investigated.

2. Representation of Crack Propagation

In this section, we introduce the adaptive element splitting procedure [1] to represent arbitrary crack growth in the finite element domain. First, 2D curved crack growth modeling is discussed, followed by the representation of a 3D crack surface with a curved crack front.

2.1 Representation of Curved Crack in 2D

To represent an arbitrary curved crack in a two-dimensional triangular mesh, the element splitting scheme [1] is utilized. When the maximum principal stress at the crack tip exceeds the material's tensile strength, the crack is assumed to propagate along the direction normal to the maximum principal stress. Then, as shown in Fig. 1, a triangular element lying along the evaluated crack direction is split into two pieces. Additionally, an element on the opposite side of the edge is also divided to preserve the topological consistency. After the splitting of continuum elements is completed, a cohesive surface element is inserted along the newly created edge, which is aligned with the crack propagation direction, to represent a new discontinuity in the finite element mesh.

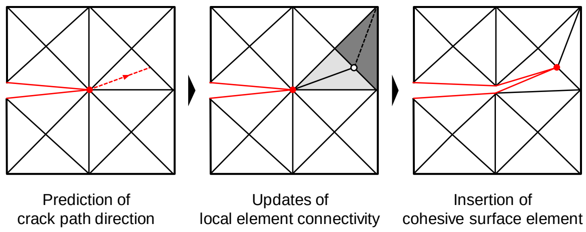


Fig. 1. Adaptive element splitting procedure for 2D curved crack.

2.2 Representation of Crack Surface with Curved Front in 3D

To model a planar crack surface with a curved front in three dimensions, the original element-splitting scheme is extended based on a tetrahedral mesh. As in the two-dimensional case, the crack initiation criterion is checked at nodes along the current crack front. Once the criterion is satisfied, the crack advancement is calculated, and then the nodes of the new crack front are generated. Based on the location of the new nodes (e.g., vertex, edge, facet or inside of tetrahedron), the tetrahedron elements are split, as shown in Fig. 2. Then, the nodes of the new crack front are connected to complete its formation. Finally, the new crack surface is created by connecting the current and new crack fronts (see Fig. 3). Note that the creation of the new crack surface is achieved by splitting tetrahedral elements that intersect the new crack surface.

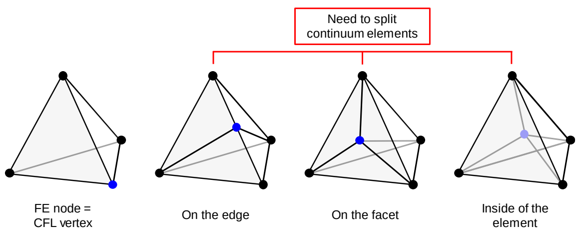


Fig. 2. 3D element splitting based on the location of the new node.

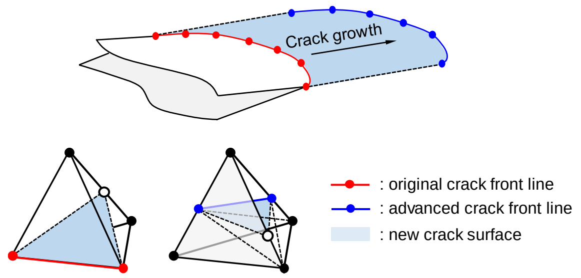


Fig. 3. Representation of 3D crack surface with curved crack front using the element splitting scheme.

3. Numerical Examples

To verify the proposed computational methodology, two benchmark problems are considered: the planar penny-shaped crack under tension and the cracked chevron-notched semi-circular bending (CCNSCB) test.

3.1 Planar Penny-shaped Crack under Tension

A cube domain with a planar circular crack is subjected to a tension load [see Fig. 4(a)]. Along the crack front, the stress intensity factor (SIF) is computed using the virtual grid-based stress recovery technique [2] and then compared to the analytical solution to verify its accuracy. As shown in Fig. 4(b), the computed results show reasonable accuracy compared with the analytical solution and other numerical methods. Based on the computed stress intensity factor, the magnitude of crack advancement is evaluated, and the growth of the crack surface is then represented using the proposed method, as illustrated in Fig. 4(c).

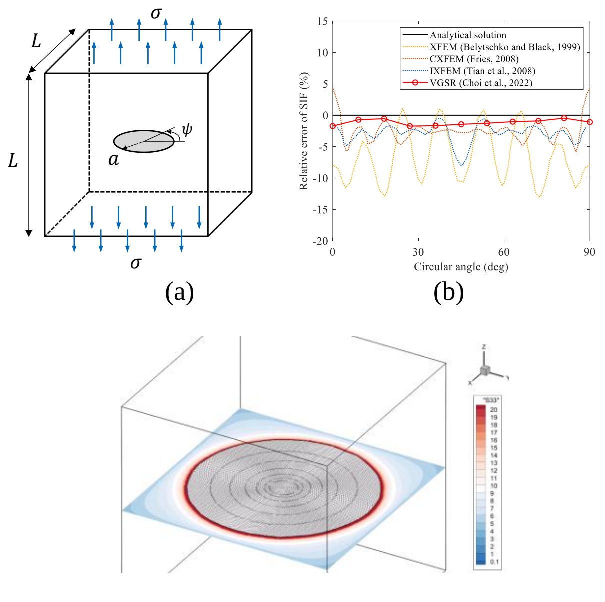


Fig. 4. Planar penny-shaped crack under tension test: (a) test configuration, (b) computed SIF values along crack front, and (c) representation of crack surface growth.

3.2 Cracked Chevron-notched Semi-circular Bending (CCNSCB) Test

As the second example, the CCNSCB test is employed, which is a well-known fracture test for measuring the mode-I fracture toughness of rock-type materials. Based on the literature [3], the test configuration, boundary conditions, and material properties are defined as shown in Fig. 5. The computed crack pattern shows that the proposed scheme can effectively represent the growth of a 3D crack surface, even when the crack front is concave or convex, and it shows good agreement with the numerical results from the literature [3] (see Fig. 6).

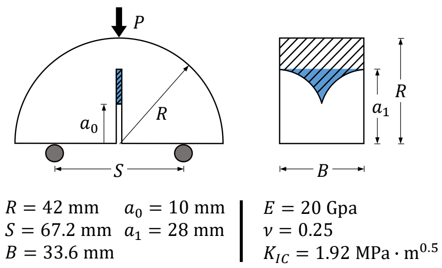
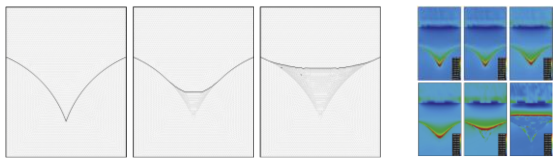


Fig. 5. Test configuration and boundary conditions of CCNSCB test.



(a) (b)

Fig. 6. Computational result of CCNSCB test: (a) computed crack pattern and (b) numerical result from the literature [3].

4. Conclusions

In this study, the two- and three-dimensional cohesive zone-based crack propagation model for nonlinear crack propagation in concrete is proposed using the adaptive element splitting scheme. To represent arbitrary crack growth in triangular (2D) and tetrahedral (3D) meshes, continuum elements are adaptively split along the crack propagation direction, and cohesive surface elements are inserted along new edges (2D) and surfaces (3D) that are aligned with the crack direction. The computational results demonstrate the accuracy and robustness of the proposed methodology and show its potential application in the assessment of structural safety for containment buildings.

ACKNOWLEDGEMENTS

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