Numerical Investigation on Nonlinear Fracture Behavior of Concrete considering Effects of Concrete Microstructures

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1. Introduction

Concrete is the one of most widely utilized materials for the construction of civil infrastructure owing to its high compressive strength, low cost, shape flexibility, etc. Additionally, reinforced concrete structures are mostly employed for containment buildings at nuclear power plants to prevent the leakage of radioactive material into the environment because reinforced concrete has a strong radiation shielding property. In general, concrete is considered a heterogeneous material that consists of cement, fine and coarse aggregates, and water. However, due to the computational cost or difficulty of numerical modeling, concrete is often assumed to be a homogeneous material in numerical analysis. In reality, the existence of coarse aggregates affects the crack propagation behavior in concrete [1] and also the leakage behavior of radioactive material through the concrete crack [2]. In this study, a computational framework is introduced to predict the nonlinear fracture behavior of concrete considering the effects of concrete microstructures. To represent arbitrary crack propagation, including crack coalescence and branching phenomena, an adaptive element splitting scheme is utilized [3]. Then, a uniaxial tension test of a concrete plate is illustrated to verify the proposed computational method.

2. Crack Propagation Modeling

This section presents a computational methodology to describe the nonlinear fracture behavior of concrete, taking into account the influence of the concrete microstructure. First, the weak form of the governing equation for quasi-static cohesive fracture is explained. Next, the element splitting procedure is illustrated for matrix cracking, crack branching, and coalescence.

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. For the constitutive behavior of solid, a compressible neo-Hookean material model is utilized, expressed as

$$\mathbf{S} = \lambda_0 \ln(\det(\mathbf{F}))\,(\mathbf{F}^{\mathrm{T}}\mathbf{F})^{-1} + \mu_0(\mathbf{I} - (\mathbf{F}^{\mathrm{T}}\mathbf{F})^{-1}) \qquad (2)$$

where λ_0 and μ_0 are the Lamé constants, and $\mathbf{F}$ is the deformation gradient tensor, respectively.

2.2 Adaptive Element Splitting Scheme

To describe arbitrary crack propagation in the matrix, the adaptive element splitting scheme is utilized, as shown in Fig. 1. In this approach, the triangular mesh is adaptively split along a calculated crack direction, and then a new crack surface is represented by inserting a cohesive surface element.

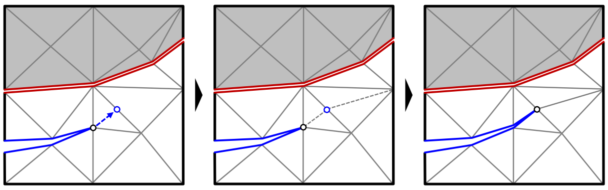

Fig. 1. Representation of arbitrary crack propagation in the matrix using the element splitting scheme.

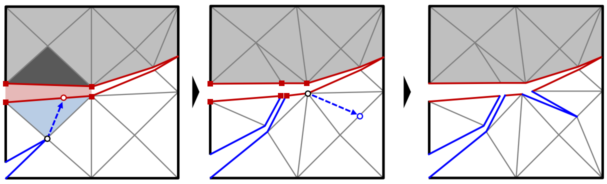

Fig. 2. Representation of crack coalescence and branching using the element splitting scheme.

To illustrate the crack coalescence, one first evaluates the crack path direction of the matrix and finds a potential junction of the matrix crack and the interfacial crack (see Fig. 2). Then, one splits the continuum element and the surface element by inserting a new node at the intersection. Additionally, another adjacent continuum element (the aggregate element) also needs to be split to maintain topological consistency. After all the element splits are completed, one inserts a new cohesive element along the generated edge in the matrix, and the crack coalescence is represented. For the crack branching representation, one checks the maximum principal stress of adjacent nodes on interfacial cracks. If there are nodes satisfying the crack growth criterion of the matrix, one splits the corresponding matrix elements along the evaluated crack propagation direction and inserts cohesive elements for the representation of crack branching.

3. Computational Example

To verify the proposed computational framework, a uniaxial tension test of a concrete plate is employed. The geometry of a test configuration is illustrated in Fig. 3. The material properties of mortar, aggregates and interfacial transition zone (ITZ) are summarized in Table 1.

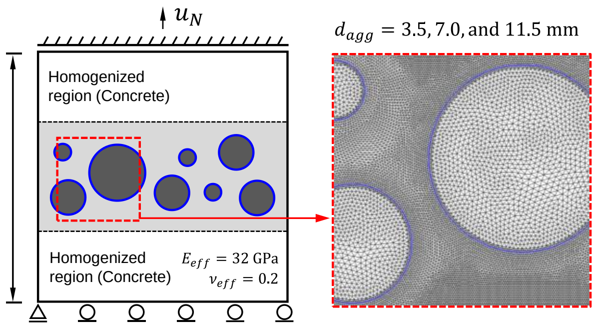

Fig. 3. Test configuration of the uniaxial tension test.

Table 1. Material properties for the concrete plate.

Phases	Mortar	Aggregate	ITZ
Elastic modulus	25 GPa	70 GPa	-
Poisson's ratio	0.2	0.2	-
Tensile strength	4.0 MPa	-	2.0 MPa
Fracture Energy	0.06 N/mm	-	0.03 N/mm

A computational result of the crack path is plotted in Fig. 4. The microcracks are initially generated at interfaces between the matrix and the aggregates and propagate in a horizontal direction. As the load increases, lots of microcracks are observed, and they merge together, which leads to macrocracks. After the macrocrack forms, no more generation of microcracks is observed, and the macrocracking behavior dominates. The computed stress versus displacement curve is illustrated with the experimental and numerical results for comparison purposes, as shown in Fig. 5. The computational results show that the overall responses, including the peak stress and the softening behavior, are within the range of the reported results.

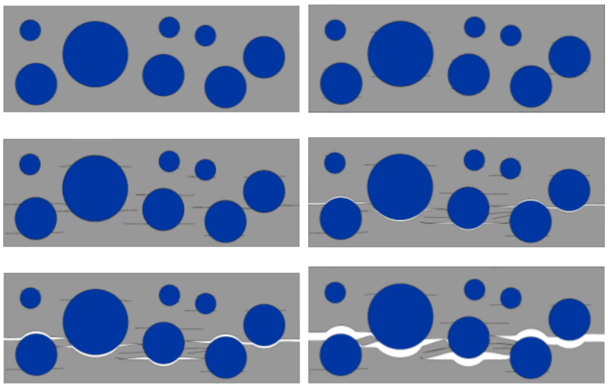

Fig. 4. Crack evolution process for square concrete specimen.

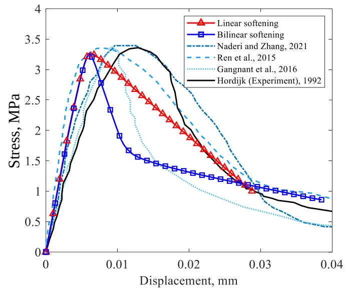

Fig. 5. Stress versus displacement curve for the uniaxial tension test of square concrete specimen.

4. Conclusions

In this study, a computational framework is presented to predict and represent the complex crack behavior of concrete composites, including mortar cracking, ITZ cracking, and crack interactions between those two failure mechanisms. By using the adaptive element splitting scheme, the matrix cracking in the mortar, as well as the crack branching and coalescence occurring along the aggregate-mortar interfaces, are accurately represented. The uniaxial tension test of the concrete plate is solved using the proposed computational framework, and the computed result is well matched with the experimental and numerical results from the literature.

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