Numerical Analysis of Concrete Behavior under Water Pressure using a Phase-field Fracture Model

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1. Introduction

The behavior of concrete structures is influenced by water pressure. Water pressure acting on cracks accelerates crack propagation and reduces the safety of the structure. In Refs. [1, 2], wedge splitting tests under water pressure were conducted, and fracture properties were experimentally obtained. However, due to the heterogeneity of concrete, conducting experiments to analyze its response necessitates numerous trials. To address this challenge, simulations, complementing experiments, can effectively reduce the time and effort required. In this study, we aim to predict the tensile strength and crack patterns of concrete specimens under water pressure. The results can be used to assess the performance of nuclear power plant containment buildings under scenarios of increased internal pressure during severe accident.

2. Methods and Results

The tensile strength and crack patterns of concrete specimens under water pressure were predicted using a poremechanics based phase-field fracture model [3]. Simulations for the wedge splitting test were conducted under two conditions, such as no pressure and the highest water pressure (0.9 MPa) cases. The input modeling parameters were calibrated by comparing the strengths with the experimental results in Refs. [1, 2]. Using the parameters, a simulation was conducted under intermediate pressure (0.5 MPa), and the results were compared.

2.1 Phase-field Fracture Model

The phase-field fracture model was implemented in the fluid-solid interaction simulation. The model enables the simulation of crack initiation, branching and merging for arbitrary complex shape of structures, and is thus widely used in modeling crack propagation. Detailed explanations are provided in Ref. [3], while only a brief description is presented below. The crack phase field d takes values between 0 (unbroken state) and 1 (fully broken state), representing the damage state. The cracks are represented as regularized cracks with a diffusive crack width l as shown in Fig. 1. The governing equations for this coupled multi-physics problem from linear momentum balance, fluid mass balance, and evolution of crack phase field are:

$$(1)\ \mathrm{div}[\boldsymbol{\sigma}] + \bar{\gamma} = \mathbf{0}$$
$$(2)\ \dot{\theta} + \mathrm{div}[\boldsymbol{h}] - \bar{s} = 0$$
$$(3)\ \eta\dot{d} - l^2\nabla^2 d + (1+\mathcal{H})d - \mathcal{H} = 0$$

where $\boldsymbol{\sigma}$ is the stress tensor, $\bar{\gamma}$ is the body force, θ is the fluid volume ratio, $\boldsymbol{h}$ is the fluid volume flux vector, $\bar{s}$ is the prescribed fluid per unit reference, η is the viscosity, and $\mathcal{H}$ denotes the crack driving force.

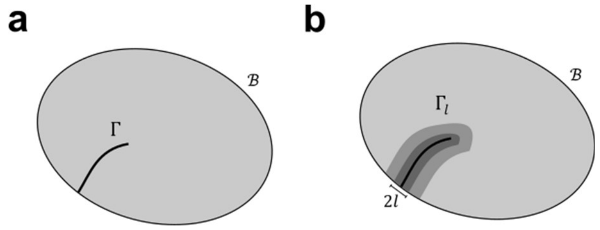

Fig. 1. A schematic of regularized crack. (a) Sharp crack, (b) regularized crack.

2.2 Wedge Splitting Test

In Refs. [1, 2], wedge splitting tests were performed on specimens with a size of 300 mm under various water pressures. The specimen details and boundary conditions are shown in Fig. 2. The responses from simulations and experiments were compared, and the input material parameters were adjusted. At first, a comparison was made under no pressure, and input parameters such as tensile strength σ_t and slope parameter ζ were determined. Subsequently, simulations were conducted with a water pressure of 0.9 MPa, and a parametric study on fluid-solid interaction parameters such as Biot's modulus and Biot's coefficient was performed.

Comparing results with Biot's modulus ranging from 0.01 to 10 GPa, a value of 1 GPa was selected to be consistent with the order of magnitude presented in Ref. [4]. Subsequently, a parametric study on Biot's coefficient, ranging from 0.1 to 1, was conducted. The value that most closely reproduce the experimental results was selected, and the determined input modeling parameters are shown in Table I.

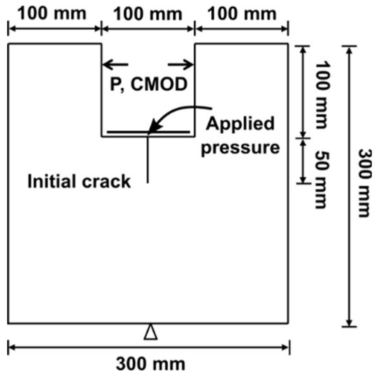

Fig. 2. Geometry and boundary conditions of wedge splitting test specimen [1].

Table I: Material properties and input parameters

Parameter		Value
E	Young's modulus	20 GPa
ν	Poisson's ratio	0.2
σ_t	Tensile strength	2.9 MPa
l	Diffusive crack width	$2h$ (h: element size)
M	Biot's modulus	1.0 GPa
b	Biot's coefficient	1.0
K	Spatial permeability	1.0×10^{-9} m^{3}s/kg
K_c	Spatial permeability in fracture	1.0×10^{9} m^{3}s/kg
ζ	Slope parameter	0.1

A simulation was conducted with a water pressure of 0.5 MPa using the parameters. The load vs. CMOD responses from the simulations are shown in Fig. 3. The peak load from the experimental result, indicated by dashed lines in Fig, 3, is similar to the predicted peak load from the simulation under a water pressure of 0.5 MPa. Through simulations, it is possible to predict the experimental results of strength reduction in concrete specimens due to water pressure acting on the cracks.

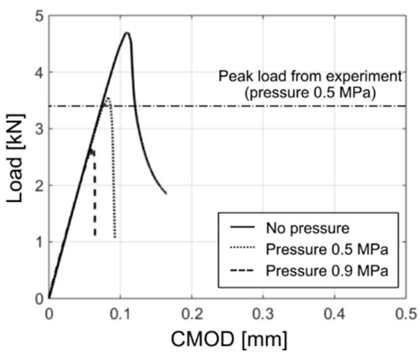

Fig. 3. Load vs. CMOD from simulations.

2.3 Uniaxial Tension Test

A virtual specimen with a through crack, due to internal pressure, was generated with the concrete microstructure, and direct tension simulations were conducted. The microstructure was modeled using the specimen in Ref. [5]. The virtual specimen has a size of 24 mm, and the parameters shown in Table I were used. The crack pattern is shown in Fig. 4, where cracks, highlighted in red. It propagates around the aggregates.

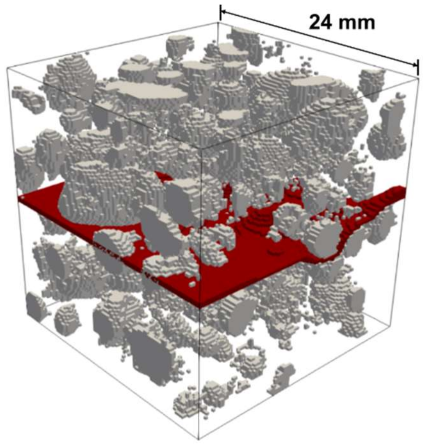

Fig. 4. Crack propagation. (Note: cracks are visualized in red, and the gray regions represent aggregates.)

3. Conclusions

This study shows the prediction of strength reduction and crack propagation in concrete specimens under mechanical loading with water pressure. A phase-field fracture model was implemented, and the simulation using the model can reproduce the experimental results. Using the concrete microstructures, the behavior of concrete specimens was predicted. With further studies, it can be possible to predict the direction of crack propagation under fluid pressure and microstructures. It is expected that this approach can be applied to evaluating the performance of a nuclear power plant.

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