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Microstructure-based Fluid-Solid Coupled Simulation of Concrete

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1. Introduction

The containment building of a nuclear power plant plays a critical role in preventing the leakage of radioactive material in the event of a major accident. Therefore, it is essential to evaluate the performance of the containment building in scenarios involving extreme internal pressures. Concrete structures are weak in tension and prone to cracking. These cracks can allow fluids to permeate and decrease the performance of the structure. To predict the behavior of containment buildings under extreme internal pressure, this study aims to compare the behavior of concrete specimens with and without fluid pressure acting on their cracks. The results can be applied to radiological environmental impact assessments for containment buildings under severe accident scenarios.

2. Methods and Results

A poromechanics based phase-field fracture model was used to predict the tensile strength and crack pattern of concrete specimens under fluid pressure [1]. In Refs. [2, 3], wedge splitting tests were performed, where concrete specimens were subjected to displacement-controlled loading, with varying levels of water pressure applied to the notches. The experimental results were used to calibrate the modeling parameters (i.e., Biot's modulus, Biot's coefficient). Using these parameters, single edge notch (SEN) tension test simulations were conducted on concrete specimens containing aggregates. Then, the specimens were assumed to represent interior elements of the containment building, and simulations with internal pressure causing membrane forces were conducted to predict the performance of concrete in the containment building.

2.1 Wedge Splitting Test

Wedge splitting tests in Refs. [2, 3] were performed on 300 mm specimens at water pressures up to 0.9 MPa. The specimen details and boundary conditions are shown in Fig. 1. The modelling parameters, based on Ref. [1], were calibrated by comparing the experimental and simulation results under two extreme conditions: no pressure and a pressure of 0.9 MPa. Initially, the tensile strength σ_t was determined by comparing the results obtained under no-pressure conditions. Next, a parametric study was performed to determine of the fluid-solid interaction parameters such as Biot's modulus and Biot's coefficient at a pressure of 0.9 MPa.

Biot's modulus selected as 1 GPa to be consistent with the magnitude reported in Ref. [4]. A parametric study was then performed by varying the Biot's coefficient in the range of 0.1 to 1, and the value that best reproduced the experimental results was selected. The determined input modelling parameters are presented in Table I.

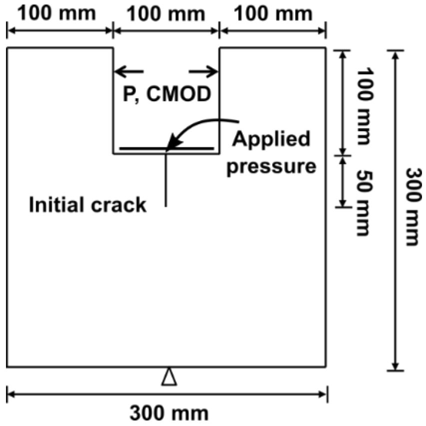

Fig. 1. Dimensions and boundary conditions of specimen [2].

Table I: Material properties and input modeling parameters

Parameter		Value
E	Young's modulus	20 GPa
ν	Poisson's ratio	0.2
σ_t	Tensile strength	7 MPa
l	Diffusive crack width	$2h$ (h: element size)
M	Biot's modulus	1.0 GPa
b	Biot's coefficient	0.9
K	Spatial permeability	$1.0\ \times 10^{-9}$ m^{3}s/kg
K_c	Spatial permeability in fracture	$1.0\ \times 10^{9}$ m^{3}s/kg
ζ	Slope parameter	1.0

2.2 SEN Tension Test

SEN tension tests were conducted using the aggregate microstructures to confirm the plausibility of modeling 3D crack propagation in concrete specimens. The aggregate microstructures from Ref. [5] were used. Two specimens with different aggregate ratios were analyzed with and without fluid pressure of 0.9 MPa, and the strength reduction rate and crack patterns were compared.

It was observed that fluid pressure does not have a significant effect on crack patterns. The crack patterns obtained from the simulations are shown in Fig. 2. However, the rate of strength reduction due to fluid pressure acting on the crack decreased linearly as the aggregate ratio increased. Thus, it is confirmed that the applied pressure on cracks significantly reduces the concrete strength.

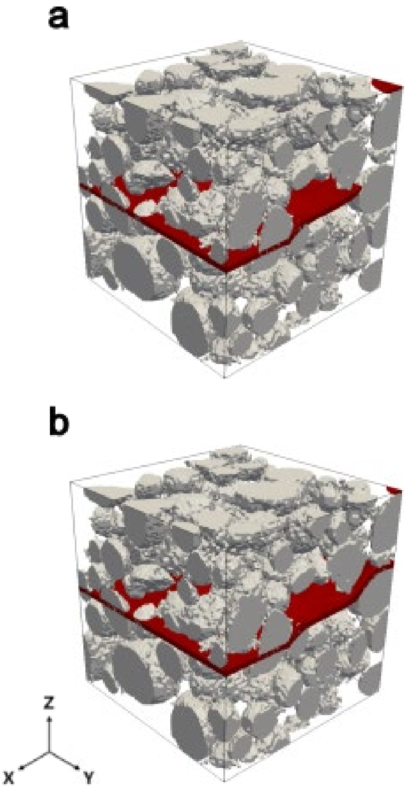

Fig. 2. Simulated crack patterns at the time of fully cracking in a specimen under fluid pressure. (a) Without pressure, (b) with pressure conditions. (Note: Cracks are highlighted in red, and aggregates are shown in gray).

2.3 Coupled Simulation of Concrete Specimen in Containment Building

To predict the behavior of the containment building under extreme internal pressure conditions, coupled simulations were performed with internal pressure of 2 MPa, which is about five times the design pressure of 0.39 MPa [6]. The dimensions of the containment building model, with a radius of 24.1 m and a thickness of 1.2 m, were used. By simply approximating the wall of containment building as a thin-walled cylindrical pressure vessel, displacement loads were applied from the stress values as:

$$(1)\ \Delta_1 = p \times \frac{rL}{Et}$$

$$(2)\ \Delta_2 = p \times \frac{rL}{2Et}$$

where p is the applied pressure, r is the radius of containment building, L is the length of concrete specimen, and t is the thickness and E is the equivalent stiffness of the wall of containment building. The specimen geometry and boundary conditions are shown in Fig. 3.

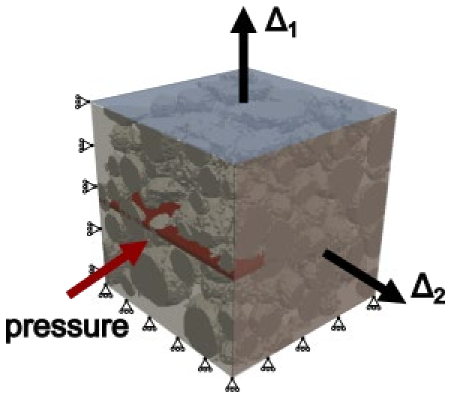

Fig. 3. Microstructure and boundary conditions of concrete.

3. Conclusions

In this study, the performance of concrete specimens under fluid pressure conditions was evaluated using a phase-field fracture model. Aggregate microstructures were used to determine 3D crack propagation, and the effect of fluid pressure was investigated. The model was applied to compare the performance of concrete specimens in containment buildings subjected to extreme internal pressure. This approach is expected to be useful for evaluating the performance of structures under fluid pressure.

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