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# A Numerical Phase-field Approach for Evaluating Cavity Effects in Concrete Structures

Donghwi Eum [a], Tong-Seok Han [a*]
[a]*Yonsei Univ., Seoul 03722, Republic of Korea*
[*]*Corresponding author: tshan@yonsei.ac.kr*

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## 1. Introduction

The containment building plays a crucial role in preventing the leakage of radioactive materials. Therefore, evaluating its structural safety is essential. Under severe accident scenarios involving extreme internal pressure, fluid pressure coupled with mechanical loads reduces the structural performance of the containment building. However, experimental evaluation of performance of such coupled problems requires considerable time and effort. To address this issue, this study employs a simulation-based approach, which can efficiently evaluate structural behavior and supplement experimental studies.

## 2. Methods and Results

A poromechanics-based phase-field fracture model was implemented to solve the coupled problem [1]. To calibrate the model, wedge splitting test simulations under applied pressure were performed. In Ref. [2], wedge splitting tests with varying water pressures were conducted, and the input modeling parameters were calibrated against the corresponding experimental responses. Using these calibrated parameters, tensile analyses were conducted on walls containing cavities of different geometries.

### *2.1 Phase-field Fracture Model*

To predict tensile strength and crack propagation under fluid pressure, a phase-field fracture model was used [1]. This approach enables the capture of crack initiation, propagation, branching and coalescence. In the model, the crack phase field $d$ ranges from 0 to 1, where $d = 0$ represents the uncracked state and $d = 1$ represents the fully cracked state. The cracks are regularized with a diffusive crack width $l$. The model simultaneously solves three governing equations: linear momentum balance, fluid mass balance, and crack phase-field evolution.

In this study, the crack phase-field evolution equation was modified with the quadratic softening degradation model [3] to reproduce the experimental responses in Ref. [2]. The degradation function $g(d)$ from Ref. [3] is:

(1) $g(d) = (1-d)^2/\{(1-d)^2 + md(1+pd)\}$

where $m$ is a constant ($\geq 1$) and $p$ is the softening parameter ($\geq 1$).

The governing equations are expressed as follows:

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

where $\boldsymbol{\sigma}$ is the stress tensor, $\bar{\gamma}$ is the body force, $\theta$ is the fluid volume ratio, $\boldsymbol{h}$ is the fluid volume flux vector, $\bar{s}$ is the prescribed fluid per unit reference, $\eta$ is the viscosity, $\xi$ is a parameter ($= 3g_c/8l$), $g_c$ is the fracture energy, and $\mathcal{H}$ denotes the crack driving force.

### *2.2 Model Calibration*

Wedge splitting tests under various water pressures were conducted [2]. The specimen size was 300 mm with a thickness of 100 mm. The specimen geometry and boundary conditions are shown in Fig. 1. The proposed phase-field fracture model was used to simulate the wedge splitting tests, and the input parameters were calibrated using experimental results obtained from tests without pressure and with an applied pressure of 0.9 MPa. The fluid-solid interaction parameters, Biot's modulus $M$ and Biot's coefficient $b$, were set to 100 MPa and 1.0, respectively, following Refs. [4, 5]. The determined input parameters are summarized in Table 1. Fig. 2 shows the fitting results. In the figure, the experimental results are plotted in black, and the numerical results are plotted in blue. Because fluid pressure was alternately applied and removed during the experiments, the conditions differed from those in the simulations, and a perfect fit could not be obtained. However, the descending branch exhibits a similar trend.

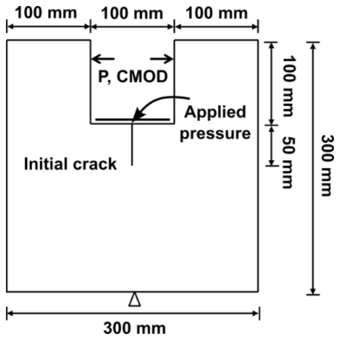


Fig. 1. Schematic of the wedge splitting test and its boundary conditions [2].

Table I: Input modeling parameters

| | Value (without pressure) | Value (with pressure) |
|---|---|---|
| $E$ | 20 GPa | 20 GPa |
| $\nu$ | 0.2 | 0.2 |
| $\sigma_t$ | 3.0 MPa | 3.0 MPa |
| $l$ | $2h$ ($h$: element size) | $2h$ ($h$: element size) |
| $M$ | - | 100 MPa |
| $b$ | - | 1.0 |
| $K$ | - | $1.0 \times 10^{-9}$ m$^3$s/kg |
| $K_c$ | - | $1.0 \times 10^{9}$ m$^3$s/kg |
| $g_c$ | 0.08 N/mm | 0.04 N/mm |
| $p$ | 6 | 8 |
| $\zeta$ | 1.0 | 1.0 |

(Note: $E$ is the Young's modulus, $\upsilon$ is the Poisson's ratio, $K$ is the spatial permeability, $K_c$ is the spatial permeability in crack, and $\zeta$ is the slope parameter.)

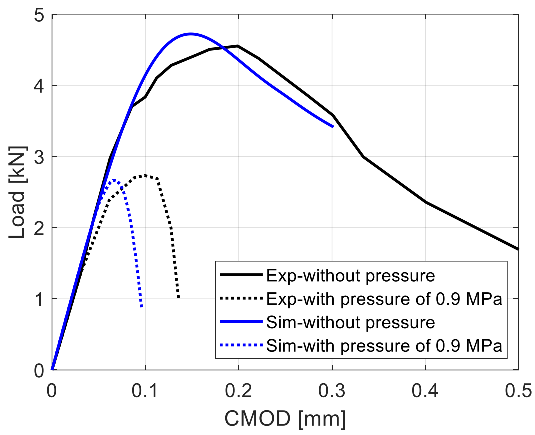


Fig. 2. Load-CMOD curves from experiment and simulation. (Note: Exp and Sim denote experimental and simulation results, respectively.)

*2.3 Model Application*

In Ref. [6], the impact of concrete voids on prestressed concrete containment vessel (PCCV) was investigated using the void discovered at Hanbit Nuclear Power Plant Unit 4 in Korea, which measured 331.3 cm in width, 38-97 cm in height, and 4.5-157 cm in depth. Two types of postulated voids, rectangular and wedge shaped, were modeled, and the responses of PCCV with and without voids were compared. To further evaluate the influence of internal cavity geometry on structural performance, a virtual concrete wall was modeled. Direct tensile simulations were then performed under coupled mechanical loading and fluid pressure.

## 3. Conclusions

This study implemented a phase-field fracture model with a modification to the crack evolution equation. The model was calibrated using wedge splitting test results. Based on the calibrated parameters, direct tensile simulations of a virtual concrete wall were performed. The analysis examined the influence of cavity geometry on structural performance. This approach is expected to be applied to the structural safety assessment of nuclear power plant containment buildings under severe accident scenarios.

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