12^{th} International Conference on Fracture Mechanics of Concrete and Concrete Structures
FraMCoS-12
B.L.A. Pichler, Ch. Hellmich, P. Preinstorfer (Eds)

https://doi.org/10.21012/FC12.1113
MS05-2:1

FLUID-SOLID COUPLED CRACK PROPAGATION SIMULATION OF CONCRETE MICROSTRUCTURE

D. EUM[1], **S.-Y. KIM**[1] **AND T.-S. HAN**[1*]

[1]Department of Civil and Environmental Engineering, Yonsei University
Seoul, Republic of Korea
*e-mail: tshan@yonsei.ac.kr

Key words: Fluid-solid interaction, Crack propagation, Concrete microstructure, Phase-field fracture model, Coupled problem

Abstract. Due to difficulties in performing fluid-solid coupled crack propagation experiments of concrete, simulations can provide significant insight into complex behaviors of concrete and structures. However, the simulation of concrete responses with microstructural features under fluid-solid coupled crack propagation is still a challenging task. In this study, a poromechanics based phase-field fracture model was implemented. The flow through concrete and crack was assumed to be laminar, where Darcy and Poiseuille flows were adopted for the concrete matrix and cracks, respectively. The modeling parameters were calibrated to wedge splitting test experiments subjected to fluid pressure. The calibrated model was then applied to simulate the responses of concrete specimens with two-phase microstructures consisting of mortar and large aggregates. The reduction in strength due to fluid pressure was identified, and the effect of aggregates on the mechanical responses of concrete was analyzed. It is confirmed that the implementation of the poromechanics based phase-field fracture model can be successfully used to investigate the fluid-solid coupled mechanical behaviors of concrete considering complex microstructures of aggregates.

1 INTRODUCTION

Concrete structures are utilized in diverse environments and are often exposed to external factors that affect their performance. Fluid pressure acting on cracks can accelerate material damage and significantly reduce structural safety. In structures like dams and offshore facilities, where fluid pressure plays a critical role, understanding the interaction between fluid and solid is essential for accurately predicting deformation and failure behavior.

Evaluating structural performance through experiments alone is challenging due to high costs and time requirements. To address this issue, multi-physics coupled simulations can supplement experimental results to enable effective performance prediction of structures under fluid pressure. In this study, a phase-field fracture model was implemented and applied to concrete microstructures to analyze the effects of fluid pressure.

2 PHASE-FIELD FRACTURE MODEL

Phase-field fracture models have been widely used to model complex crack propagation. In this study, a poromechanics based phase-field fracture model was implemented for modeling crack propagation and evaluating mechanical properties. More details can be found in Ref. [1], and only a brief description is given below.

In the model, the time-dependent crack phase field d is defined on the solid. It represents the damage state, with $d = 0$ indicating an unbroken state and $d = 1$ denoting a fully broken 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 problem are as follows:

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

where $\boldsymbol{\sigma}$ denotes the stress tensor, $\bar{\boldsymbol{\gamma}}$ represents the body force, θ is the fluid volume ratio, $\boldsymbol{h}$ is the fluid volume flux vector, $\bar{s}$ refers to the prescribed fluid volume per unit reference, η is the viscosity and $\mathcal{H}$ indicates the crack driving force. The three governing equations are converted into weak forms, and the solutions are obtained through the finite element analysis procedure.

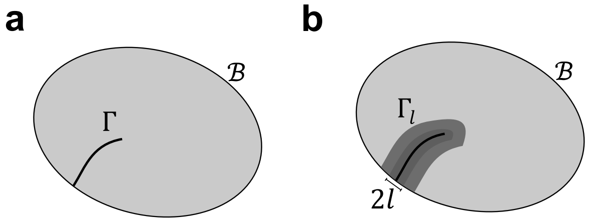

Figure 1: A schematic of regularized crack. (a) Sharp crack (Γ), (b) regularized crack (Γ_l).

3 MODEL CALIBRATION

3.1 Experiment

The model calibration was performed using the results of wedge splitting test experiments under fluid pressure. In Refs. [2,3], wedge splitting tests were performed by applying different levels of water pressure to the initial notch. The concrete specimens were 300 × 300 × 100 mm in size, as shown in Fig. 2. The experiments were conducted under six conditions, ranging from no water pressure to 0.9 MPa, to study the behavior of concrete specimens under the fluid pressure.

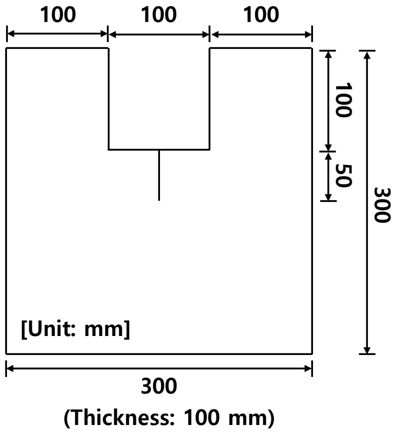

Figure 2: Specimen geometry.

3.2 Simulation

Simulations were performed under the plane strain condition, which is valid for specimens with sufficient thickness and a constant cross-section. This approach was chosen to improve the efficiency of the simulation, and the results were compared with the experimental results. The process for determining the input modeling parameters is as follows. First, the input tensile strength σ_t, a fracture parameter, was calibrated by matching the simulation results with experimental data under conditions without fluid pressure.

Next, a fluid pressure of 0.9 MPa was applied, and the resulting strengths were used to determine the fluid-related parameters, Biot's modulus (M) and Biot's coefficient (b). These parameters influence the interactions between fluid and solid deformation. A parametric study was conducted by varying Biot's modulus from 0.01 to 10 GPa, resulting a difference of approximately 10%. For consistency, the value of 1 GPa was selected based on the value provided in Ref. [4]. Then, Biot's coefficient was calibrated to 0.9 reproducing the peak load of the 0.9 MPa pressure specimen. The calibrated responses from simulations are shown in Fig. 3. The solid line labeled 'Reference' represents the case without fluid pressure, while the dashed line labeled '0.9 MPa' represents the case with fluid pressure. The modeling parameters are shown in Table 1. According to Ref. [5], the diffusive crack width was determined to be twice the element size h.

Table 1: Input modeling parameters

Parameter	Name	Value
E	Young's modulus	20 GPa
ν	Poisson's ratio	0.2
σ_t	Tensile strength	7.0 MPa
l_c	Diffusive crack width	6.0 mm (=2h)
M	Biot's modulus	1.0 GPa
b	Biot's coefficient	0.9
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	1.0

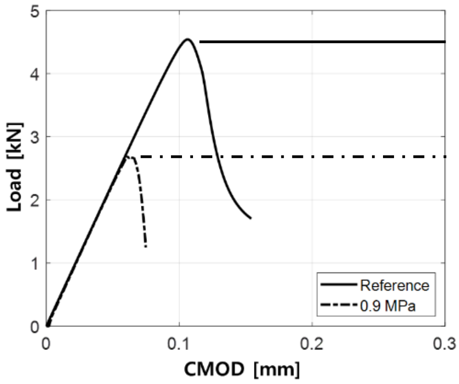

Figure 3: Load vs. CMOD curves from simulation. (Note: The peak loads from the experiments [2] are represented by a horizontal line).

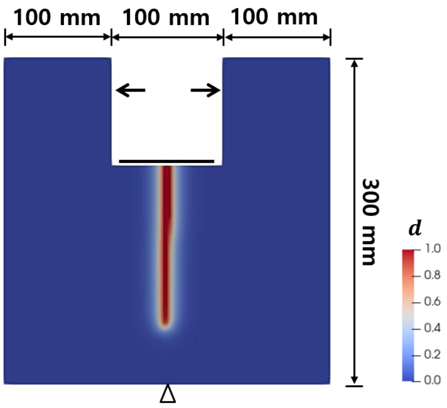

Figure 4: Crack profile from wedge splitting test under fluid pressure.

The simulated crack profile of a wedge splitting test with a fluid pressure of 0.9 MPa applied to the initial notch using the parameters given in Table 1 is shown in Fig. 4. Since the specimen is a homogeneous model with no microstructure considered, the crack shown in red propagates in a straight line.

4 MODEL APPLICATION

For investigating the strength reduction due to fluid pressure and the 3D crack propagation in concrete specimens, the model was applied to two-phase microstructures composed of mortar and aggregate.

4.1 Single edge notched (SEN) specimen

Concrete microstructures were used to generate single edge notched specimens. The microstructures were obtained from micro-CT images with a resolution of 30 μm/pixel, and further details are provided in Ref. [6]. SEN tension tests were performed using specimens with aggregate ratios of 27% and 36%, respectively. The specimen has a size of 24 mm, with an initial notch of 6 mm (one-quarter of the specimen size) placed at the center. The virtual SEN specimens are shown in Fig. 5. To examine the effect of fluid pressure on strength reduction based on aggregate ratios, a homogeneous specimen without aggregates was also generated.

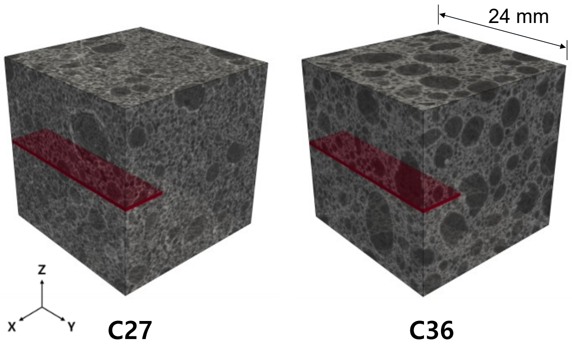

Figure 5: SEN specimens. (Note: The specimens are labeled as C27 and C36 based on the aggregate ratio. In the microstructures, the darkest regions represent the aggregates, and the initial notch is highlighted in red).

4.2 Finite element method

A coupled analysis incorporating fluid pressure and mechanical loading was conducted using the SEN specimen shown in Fig. 5. The setup involved applying a displacement load at the top of the microstructure along the z-axis at $z = 24$ mm, and a fluid pressure of 0.9 MPa at the left surface ($x = 24$ mm) including the notch. A schematic of test setup is shown in Fig. 6.

The diffusive crack width, a modeling parameter of the phase-field fracture model, was set to twice the element size [5]. The SEN tension tests were performed with a mesh of one million elements using the calibrated parameters.

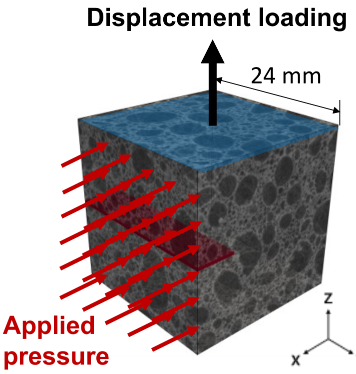

Figure 6: A simulation setup for the C36 specimen.

5 RESULTS

The analysis results for three specimens with different aggregate ratios were compared under conditions with and without a fluid pressure of 0.9 MPa. Strength reduction was observed under fluid pressure, with the rate of reduction varying with the aggregate ratio. For instance, the strength reduction due to fluid pressure was approximately 24% for the C00 without aggregates, compared to about 14% for the C36 with a higher aggregate ratio. The load vs. displacement curves for the three specimens are shown in Fig. 7. The reduction rate decreased linearly with increasing aggregate ratio. It confirms that fluid pressure acting on cracks significantly reduces concrete strength.

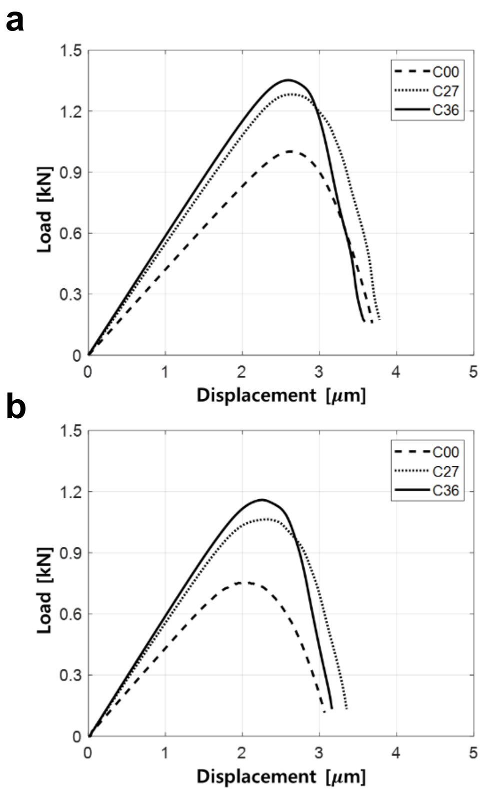

Figure 7: Load vs. displacement curves from simulation. (a) Without pressure, (b) with pressure.

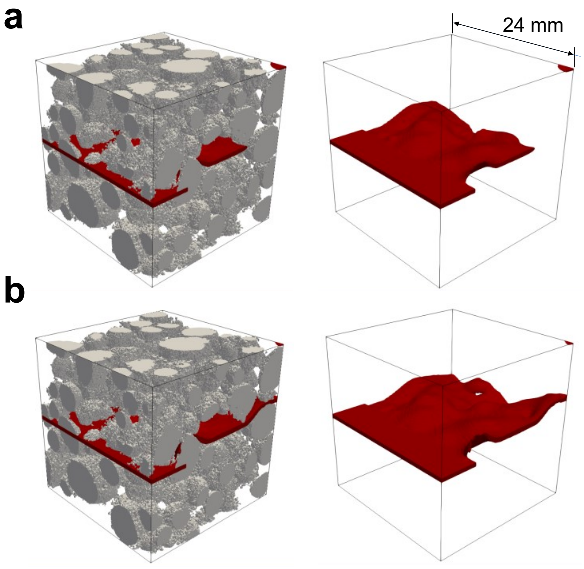

Figure 8: Crack profile comparison. (a) Without pressure, (b) with pressure.

The crack profile obtained from the simulation for C36 at the time of fully cracking under pressure is shown in Fig. 8. In the figure, the brightest phase represents the aggregates, and the crack phase field d larger than 0.9 is highlighted in red. It can be observed that the crack propagates around the aggregates.

6 CONCLUSIONS

This study used a multiphysics approach based on poromechanics to evaluate concrete strength under fluid pressure. A phase-field fracture model was implemented and calibrated using the experimental results. Concrete microstructures were used to analyze 3D crack propagation, and the effect of fluid pressure was investigated. Through the simulation, it was found that the strength reduction caused by crack pressure could be predicted, and was dependent on the aggregate ratio. It is confirmed that the poromechanics based phase-field fracture model effectively predicts the fluid-solid coupled behavior of concrete, considering the complex microstructure of aggregates. It is expected that this approach is useful for analyzing the behavior of structures with fluid-induced cracks.

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