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Evaluation of Localized Liner Failure using XFEM

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1. Introduction

The containment building serves as the final barrier in the multiple protection systems of nuclear power plants. Thus, its structural integrity must be maintained to prevent the release of radioactive materials under severe accident conditions. Overpressurization test of a 1/4 scaled prestressed concrete containment vessel (PCCV) performed by Sandia National Laboratories observed multiple cracks in concrete and liner failures as internal pressure increased [1].

Since strain concentration is directly related to liner failure, realistic simulation is necessary to investigate its effects. There are several analysis methods to simulate these cracks, such as extended finite element method (XFEM) and damage mechanics. XFEM has the advantage of efficiently simulating cracks without remeshing [2]. Also, it has been often utilized to simulate multiple cracks in concrete [3].

In this study, two-step simulations were conducted using a global and local approach. The local model was focused specifically on equipment hatch (E/H) region. Using XFEM, multiple concrete cracks simulation was performed in the E/H. Finally, the effect of multiple cracks on liner failure was evaluated.

2. Analysis Model and Method

2.1 Model description and analysis method

In first step simulation, the global model consists of 10.8 m diameter concrete cylinder with a 325 mm thick wall, a 3.5 m thick foundation mat, and a 275 mm thick hemispherical dome. It incorporates 90 horizontal tendons and 108 vertical tendons with two layers of rebar. Prestress was applied in the hoop and meridional directions, maintaining the same tendon configuration as the actual structure. Body force was considered and internal pressure corresponding to limit state test of 3.3 P_d (Design pressure P_d=0.39 MPa) was applied uniformly to liner's inner surface. Nodes of the bottom surface were fixed.

In second step simulation, the local model was constructed for main penetration of PCCV, which is the E/H. Detailed modeling of anchors, stiffeners, etc. was performed to capture strain concentrations. Displacement results from the global model were applied as boundary conditions to the local model using ABAQUS sub-modeling technique [2]. Additionally, crack growth analysis was performed in the local model concrete regions where cracks occurred in the experiment [1].

2.2 Material properties

Material of concrete was assumed as linear elastic model. To simulate multiple cracks using XFEM, crack initiation of concrete was set as the maximum principal stress criterion, with a value of 3.91 MPa [1]. Elasto-plastic model with isotropic hardening was considered to represent the behaviors of rebar, liner and tendon. Details of material properties are summarized in Table 1.

Table 1: Material properties of model components

	Density [kg/m^3]	Elastic modulus [MPa]	Poisson's ratio	Yield strength [MPa]
Rebar	7,849	183,000	0.3	439
Liner	7,800	200,000	0.3	376
Tendon	7,410	200,000	0.3	1,530
Concrete	2,186	27,200	0.21	17.7

3. Numerical Assessment

3.1 Mesh sensitivity analysis and model validation

To simulate crack growth efficiently and accurately, a mesh sensitivity analysis was conducted with mesh sizes of 100 mm, 90 mm, and 80 mm in concrete regions. Figure 1 shows hoop strain of liner at 3.3 P_d for two locations of E/H.

These locations were selected based on the sites of liner failure and strain gauges in the experiment [1].

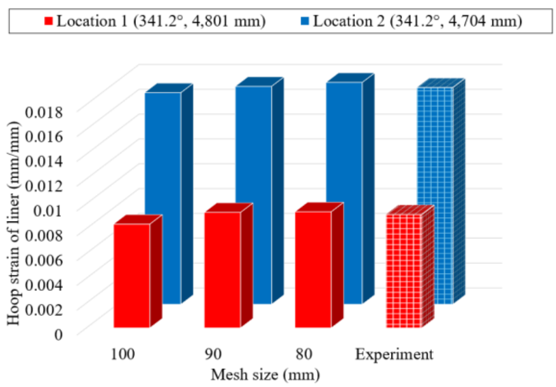

Figure 1 : Comparison of mesh sensitivity analysis results with experimental data at 3.3 P_d

Differences of hoop strain in the liner between the mesh sizes of 90 mm and 80 mm were 0.55% at location 1 and 1.78% at location 2. Therefore, mesh size of 90 mm was chosen for the simulation.

Validation for model was carried out by comparing the hoop strain at these locations with experimental results. At locations 1 and 2, differences were 1.84%, and 0.54% respectively.

3.2 Evaluation of liner failure considering multiple concrete cracks

Four specific locations where the failure was observed in the experiment were selected for evaluation of liner failure. The crack analysis results and selected locations are illustrated in Figure 2.

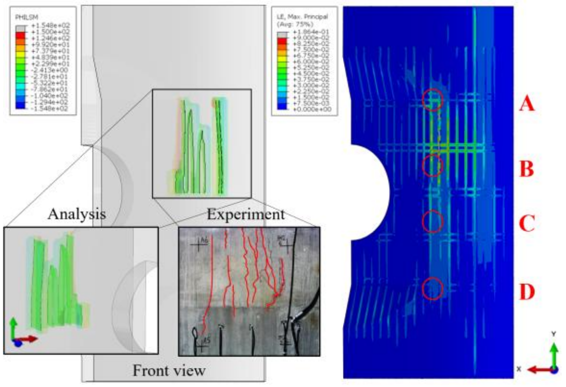

Figure 2 : XFEM-based crack growth analysis in concrete (left) and maximum principal strain distribution in liner (right)

The maximum value of the strain gauges, 0.02312 mm/mm at 2.5 P_d, where first leakage by the failure was observed in the experiment, was adopted as the failure criterion [1]. Based on this criterion, liner failure was evaluated at these four locations, as shown in Figure 3.

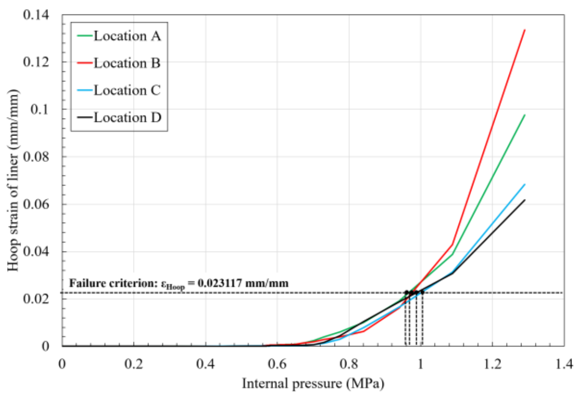

Figure 3 : Hoop strain of liner according to internal pressure

At locations A and B, failure pressures were calculated as 2.48 P_d and 2.51 P_d, respectively, which are close to the criterion. In contrast, at locations C and D, those were calculated as 2.57 P_d and 2.56 P_d, respectively. Multiple cracks were observed in concrete at locations A and B, but not at C and D. Thus, it is inferred that the strain concentration resulting from these cracks contributed to the differences in pressures. Additionally, a comparative study was performed with and without application of XFEM. Table 2 presents comparison of the results. It was found that XFEM shows, on average, 16% more comparable results compared to when it is not applied. The analysis using XFEM shows its effectiveness in capturing localized liner strain concentration. Therefore, this method is also expected to predict crack propagation in liner.

Table 2 : Comparison failure pressures between XFEM and FEM

Location	XFEM [MPa]	FEM [MPa]
A	0.969 (2.48 P_d)	1.079 (2.76 P_d)
B	0.978 (2.51 P_d)	1.265 (3.24 P_d)
C	1.005 (2.57 P_d)	1.260 (3.23 P_d)
D	0.994 (2.56 P_d)	1.129 (2.89 P_d)

4. Conclusions

In this study, the global and the local models of 1/4 scaled PCCV were developed and effect of multiple concrete cracks on liner was evaluated. The conclusions are as follows:

(1) Model validation was performed by comparing the analysis and experimental result. The liner strains at two locations showed a difference of 1.84% and 0.54%, respectively.
(2) The XFEM analysis results approximately matched the locations of concrete cracks that occurred in the actual experiment.
(3) When crack simulation was considered using XFEM, more pronounced localized liner strain concentrations occurred. As a result, more comparable failure pressure was predicted from the simulation using XFEM.

ACKNOWLEDGMENTS

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