Transactions of the Korean Nuclear Society Autumn Meeting
Changwon, Korea, October 30-31, 2025

Detailed Modeling of Containment Building Liner Plate Anchorage for XFEM-Based Crack Analysis under Internal Pressure

Sangkwon Kwak [a*], Tae-Hyun Kwon[a]
[a]*Structural and Seismic Safety Research Division, Korea Atomic Energy Research Institute,*
111, Daedeok-daero 989 beon-gil, Yuseong-gu, Daejeon, Korea
[*]*Corresponding author: skkwak94@kaeri.re.kr*

Keywords : containment structural, liner plate, crack, extended finite element method

1. Introduction

Nuclear containment structures serve as the final barrier against radiological release during severe accidents. The internal steel liner plate not only compensates for the concrete's permeability and ensures airtightness but also maintains the continuity of the pressure boundary. However, local restraint and contact-induced shear near liner anchorage details can act as triggers for initial cracking and leakage. Accordingly, explaining the behavior of the liner plate is critical for evaluating the risk of radiological release.

Since the 1970s, numerous scaled experiments have been conducted on nuclear containments. In 1979, a 1/4-scale large overpressurization test of the Ohi-3 prototype was carried out at Sandia National Laboratories (SNL) [1]. That program performed a Limit State Test (LST) and measured the leak rate versus internal pressure up to global failure, together with strains in the liner plate, reinforcing steel, tendons, and concrete, and the overall leakage. Subsequent modeling efforts developed both a full 360° 3D-shell model and an axisymmetric model, not only predicting the nonlinear response of the 1/4-scale PCCV but also exploring reliable methods to assess the effect of internal pressurization on actual PCCVs [2].

Following the Fukushima accident, the durability of the liner and containment re-emerged as a central concern for preventing radiological release. Finite-element studies employing L-angle anchorage representations reported that the liner yielded but did not fracture—an outcome attributable to the pressure level being limited to approximately $1P_d$ (design-basis accident conditions)[3]. Because modeling the entire structure with explicit anchorage details is computationally demanding, local three-dimensional FE analyses including anchorage details were constructed to estimate leakage and identify major contributors[4]; however, these works assumed no contribution from the steel liner and computed leakage solely from concrete crack width and length. In addition, XFEM-based investigations were conducted to reduce the cost and time burdens associated with remeshing during crack propagation, confirming that XFEM can reasonably analyze cracking in complex three-dimensional anchor regions[5]. Collectively, these studies leave unresolved, at ultimate internal pressure levels, the precise location of the maximum principal stress, the site of crack initiation when the liner and anchorage are explicitly considered, and the quantitative relationship between cracking and pressure. Thus, there remains an urgent need for further investigations of the liner plate's early leak-path prediction driven by microcracking and the subsequent calculation of leakage rates.

Therefore, to reduce computational costs, this study constructs a 1° cyclic-symmetry three-dimensional sector model of APR1400 in ABAQUS. The model includes frictional contact between the concrete and the steel liner plate and represents embedded anchorage details (angles and channels). This study determines the distribution of maximum principal stress, identifies the initial crack location, and estimates the crack-initiation pressure expressed as a multiple of P_d. The results are expected to support the identification of the first leak-susceptible regions in full-size containment at ultimate internal pressure and, ultimately, to inform microcrack-based estimations of radiological release.

2. Methods and Results

In this section the numerical techniques used to investigate the crack characteristics of the liner plate, Sector model and crack simulation result are described.

2.1 XFEM Configuration and Scope of Use

The objective of applying XFEM in this study is to identify the initial crack location in the vicinity of the liner plate and its anchorage without re-meshing. The base principle and feature of Extended Finite Element Method(XFEM) are shown in the related reference, which is not shown in detail here[5]. Because the angle and channel anchorage members are embedded within the concrete, any cracking in these components does not directly breach the internal pressure boundary; by contrast, leakage is expected to initiate immediately when the steel liner cracks or fractures. Accordingly, cracking was activated only in the liner plate. Crack initiation was defined by the maximum principal stress (MAXPS) criterion. The critical stress for the liner was set equal to its yield strength, reflecting our emphasis on conservative localization of the initiation site rather than precise prediction of the fracture moment. The type of damage evolution is based on power law energy damage criterion, mixed mode behavior for the power law(power=1), and linear softening was applied. The normal mode, first direction shear mode and second direction shear mode fracture energy was given as 196000N/m.

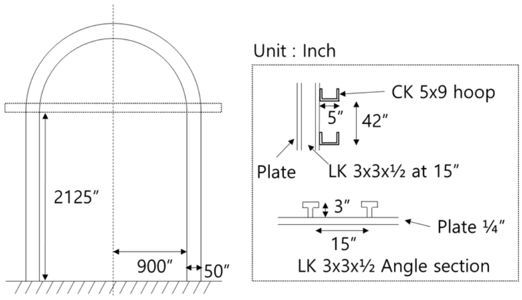

Fig. 1. APR1400 containment and the anchorage specification

2.2 APR1400 Sector Model with Cyclic Symmetry

The target containment is free-field region of APR1400 and the detailed size information is shown in Fig. 1. Following prior studies on local components and cyclic-symmetry modeling, the computational domain is a standard annular sector equal to 1° of the 360° circumference as shown in Fig. 2[4]. Material properties and damage criteria for all geometry are shown in Table 1.

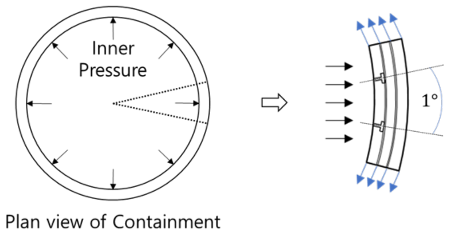

Fig. 2. Plane view of containment cylinder and component

Table 1 Material properties

Input value	Concrete	Steel
Element	Solid(C3D8R)	
Elastic modulus (GPa)	29.14	200
Poisson's ratio	0.17	0.3
Density (Kg/m^3)	2351.1	7800
Max Principal stress (MPa)	-	220.6
Normal Mode Fracture Energy (N/mm)	-	196000

The concrete, liner plate, anchorage was modeled as linearly elastic. With boundary conditions, cyclic symmetry was imposed on the two radial faces of the local sector about the cylindrical containment axis, and Z-symmetry was applied to the top and bottom faces to represent free-field conditions. To satisfy the strict periodicity and symmetric stress distribution required by cyclic symmetry, the L-angle detail was replaced with a T-angle as shown in Fig. 3. The concrete–liner interface was modeled as surface-to-surface contact with hard contact normal behavior and a penalty tangential formulation using a coefficient of friction μ = 0.4. The inner surface of the liner was subjected to a uniform internal pressure from 0 to 1.5 MPa. Regarding mesh size, whereas the reference study [4] employed a uniform 30-mm mesh, this paper refined the discretization to resolve anchorage details: approximately 100 mm for the concrete domain and approximately 5 mm for the liner plate and anchorage components.

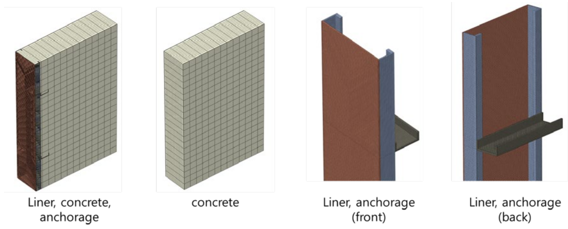

Fig. 3. Analysis model (concrete, liner, angle, channel)

2.3 Crack analysis under Internal Pressure

The maximum principal stress does not occur in the liner plate itself but peaks at the channel–angle intersection as shown in Fig. 4.

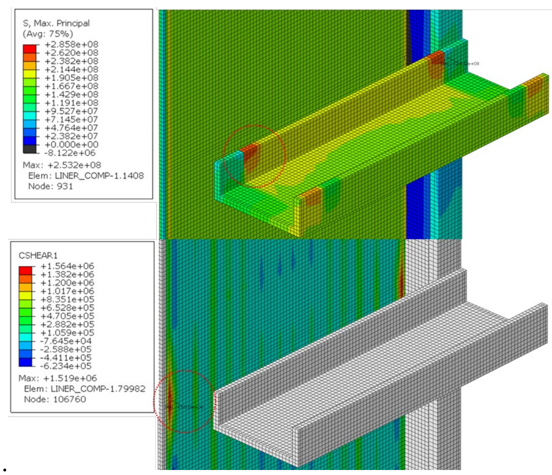

Fig. 4. Maximum principal stress and contact shear stress at crack initiation

This behavior is attributed to internal pressure acting predominantly in the hoop direction, which concentrates membrane force paths in the circumferentially continuous channel, while the geometric discontinuity at the intersection further amplifies the local stress concentration. At the beginning of cracking, the contact shear stress (CSHEAR) rises sharply in the vicinity of the liner–channel interface, consistent with the stress concentration at the same location.

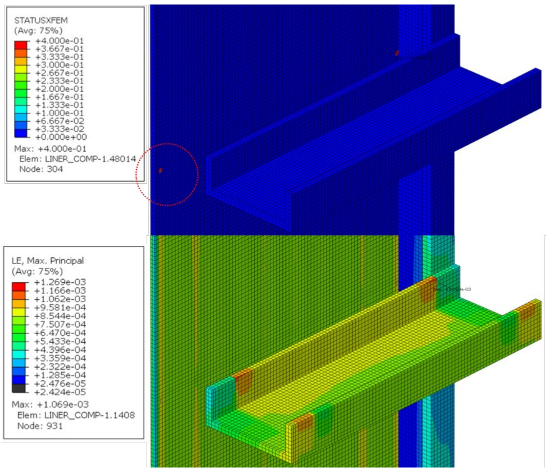

Fig. 5. Crack location and logarithmic strain at crack initiation

As shown in Figure 5, the first crack initiates in the liner plate nearest to the channel, and the accompanying logarithmic strain field corroborates that crack beginning is governed by the combined effect of hoop-stress concentration transmitted through the channel and contact shear. The crack length shows an approximately linear dependence on pressure, as shown in Fig. 6. This behavior is interpreted as the combined effect of modeling the concrete as linear elastic and restricting crack evolution to the liner plate. The brittle-fracture assumption for the steel liner, no global failure was observed at 3.632 P_d. This is attributed to energy dissipation and local confinement arising from interface friction and the cyclic-symmetry constraints, together with the omission of concrete damage, which collectively limited further crack propagation.

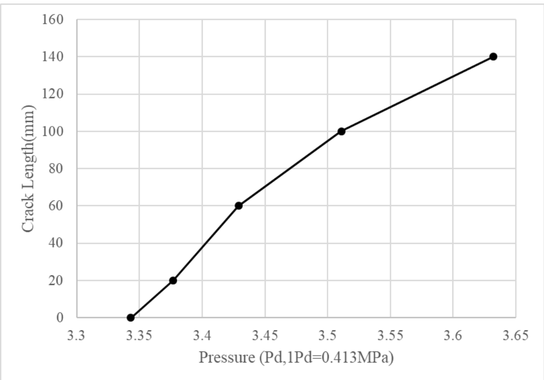

Fig. 6. Crack length-Pressure curve(Multiple of P_d)

Although crack was activated only for the liner plate in this study and formal crack assessment was therefore performed in the liner plate, the relative vulnerability among steel components, inferred from Max principal stress and CSHEAR distributions under the same loading, follows the order channel, liner plate, angle. It should be regarded as a conditional inference under the present modeling assumptions—namely, linear-elastic concrete, XFEM activation limited to the liner plate, substitution of the L-angle with a functionally equivalent T-angle to satisfy cyclic symmetry, and an interface friction coefficient of μ=0.4

3. Conclusions

In this study, a one-degree cyclic-symmetry three-dimensional sector model of the APR1400 containment was developed, modeling anchorage details and performing internal pressurization analyses with frictional contact between the concrete and steel liner. Crack characteristics employed the extended finite element method (XFEM) restricted to the liner plate, enabling identification of the initial crack location without remeshing. The maximum principal stress was found to concentrate not in the liner itself but at the channel–angle intersection; at the instant of crack initiation, contact shear stress was observed in the liner–angle interface. The first crack occurred in the liner plate adjacent to the channel, and the pressure–crack-length relation showed an approximately linear trend. Based on max principal stress and contact-shear indicators, a relative vulnerability order among the anchorage component was inferred; it should be regarded as conditional under the present modeling assumptions. Through this, we plan to include a concrete damaged plasticity (CDP) model and ductile damage evolution in liner plate, provide a quantitative characterization of the pressure–crack length, and estimate leakage rates.

ACKNOWLEDGEMENT

This work was supported by the Korea Institute of Energy Technology Evaluation and Planning(KETEP) of the Republic of Korea(NO. RS-2022-KP002846)

REFERENCES

[1] M. F. Hessheimer, E. W. Klamerus, L. D. Lambert, G.S.Rightley, and R. A. Dameron. Overpressurization Test of a 1:4-Scale Prestressed Concrete Containment Vessel Model, NUREG/CR-6810, SAND2003-0840P, Sandia National Laboratories, Albuquerque NM. March, 2003.
[2] K. Yonezawa, K. Imoto, Y. Watanabe, M. Akimoto, Ultimate capacity analysis of 1/4 PCCV model subjected to internal pressure, Nucl. Eng. Ees, 2002
[3] P. bily, A. Kohoutkova, A Numerical Analysis of the Stress-Strain Behavior of Anchorage Element and Steel Liner of a Prestressed Concrete Containment Wall, Structures, 2017
[4] Q. Fan, Z. Lu, B. Zhao, D. Jiang, Structural and functional failure mechanism of the local component of nuclear containment, Eng Structure, 2025
[5] J. Choi, T. kwon, Investigation of crack characteristics of steel linear plate of containment building using XFEM for the quantification of leakage, Transactions of Korean Nuclear Society, 2024