

Crack Assessment of Containment Building Liner Plate up to Maximum Crack Extent

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***Keywords :** containment building, liner plate, crack analysis, extended finite element method

1. Introduction

Containment buildings must retain their structural integrity under internal pressurization, and their safety performance depends heavily on the condition of the liner plate — the component that provides the primary leak-tight boundary and is directly loaded once pressure builds up inside the structure — where tensile stresses tend to concentrate wherever the plate geometry changes abruptly. Once internal pressure rises past design-basis levels toward an ultimate loading condition, these localized concentrations can trigger crack initiation and subsequent propagation through the liner plate, making the fracture response of the plate a key factor in judging how much leak-tightness margin the containment retains.

Large-scale overpressurization tests of scaled containment models, such as the 1:4-scale prestressed concrete containment vessel (PCCV) test conducted at Sandia National Laboratories for the U.S. Nuclear Regulatory Commission [1], have repeatedly identified the liner plate—rather than the surrounding concrete—as the actual source of leakage, with dozens of tears observed in the liner plate well before the concrete itself lost structural capacity. Most analytical work motivated by these tests, however, has examined the overall pressure–displacement response of the containment, leaving the local fracture behavior of the liner plate itself comparatively unexamined. Motivated by this gap, the present study uses an XFEM-based sector model, previously developed by the authors [2], to characterize how a liner plate fractures under ultimate internal pressure, focusing specifically on crack initiation, propagation, and the resulting crack area. Simulating this kind of crack growth with conventional finite element methods is complicated by the need to repeatedly remesh the crack path, which drives up computational cost and can compromise numerical stability; the extended finite element method (XFEM)[3] avoids this difficulty by letting cracks propagate independently of the underlying mesh topology.

2. Crack Area Evaluation

2.1 Summary of the Sector Model

As shown in Fig. 1, a 1-degree local model was created from the full 360-degree wall using cyclic

symmetry, thereby reducing computational load while maintaining structural representativeness.

Additionally, Z symmetry boundary condition was applied to the top and bottom of the model. Symmetry is required specifically in this axial (Z) direction because the model represents only a thin slice of the cylindrical wall's height, taken from the mid-height region where the vertical stress state repeats above and below the modeled slice. In the circumferential direction, the model is constrained by cyclic symmetry conditions applied to a 1° sector cross-section, the overall boundary conditions are consistent with the plane-strain approximation applicable to the mid-height region of the cylindrical containment wall.

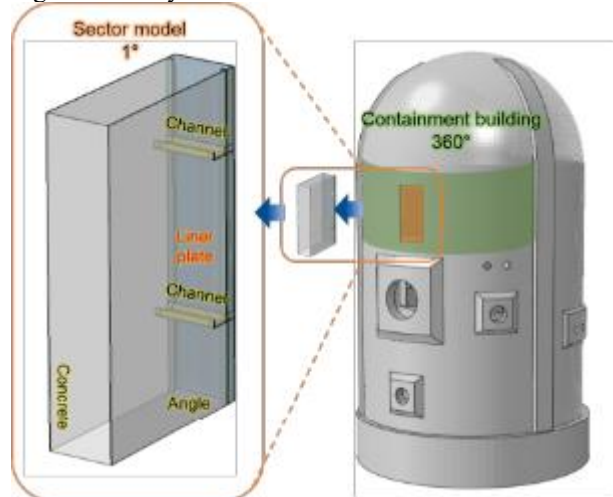


Fig. 1. 1° sector model of containment building

For this analysis, nonlinear material properties corresponding to the mechanical characteristics of each component—based on the values used in the APR1400 design—were assigned to the concrete, liner plate, channel and angle elements. The material properties used are presented in Table I, II and Fig. 2, 3.

The interface between the concrete and the steel liner plate was modeled using a node-to-surface contact method. To simulate shear force transfer across the interface, a penalty formulation with a tangential friction coefficient of 0.4 was applied.

Table I: Material properties

	Concrete	Steel
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Density (t/mm ³)	2.4E-09	7.85E-09
Young's modulus (MPa)	19,510	200,000
Poisson's ratio	0.17	0.3
Max principal stress (MPa)	-	342.61
Normal mode fracture energy (N/mm)	-	196[4]

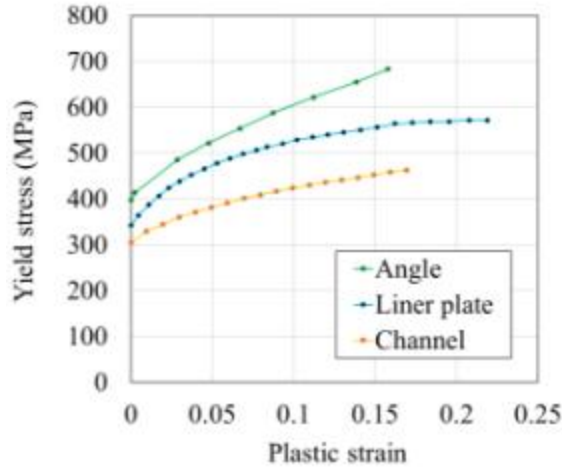


Fig. 2. Plastic properties of steel materials

Table II: Plasticity data of concrete

Dilation angle	Eccentricity	f_{b0}/f_{c0}	K	Viscosity
56	0.1	1.16	0.67	0.001

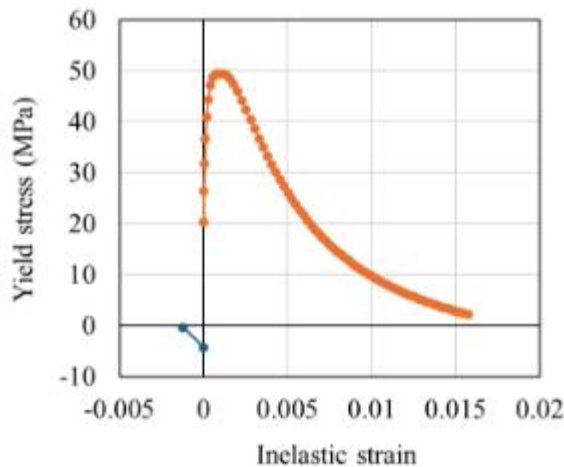


Fig. 3. Compressive and tensile behaviors of concrete

2.2 Crack Area up to the Maximum Extent

Fig. 4 shows the deformed shape of the liner plate at six representative pressure levels from 2.7 to 3.0 MPa, illustrating how the crack grows from initiation to full through-thickness penetration near the edge mesh region of angle. Fig. 5 shows the relationship between

pressure and crack area. a 6.35 mm thick liner plate divided into four element layers along the thickness direction. The crack area remains negligible up to approximately 2.7–2.8 MPa but increases rapidly thereafter, reaching a maximum of about 200 mm² near 3.0 MPa. This indicates that the crack has fully penetrated the thickness. This maximum crack area, located near the embedded angle and channel components, represents the governing local condition against which the containment's leak-tightness margin under ultimate internal pressure should be assessed.

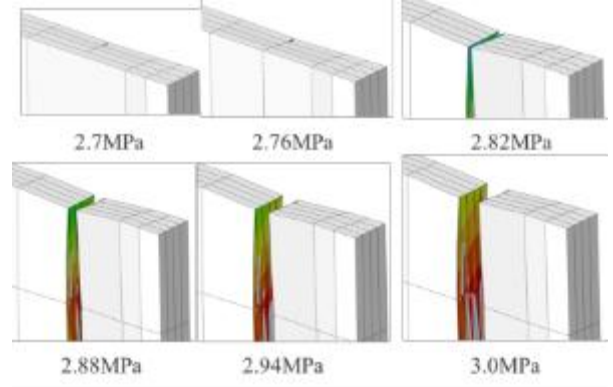


Fig. 4. Crack propagation (deformed scale factor: 100)

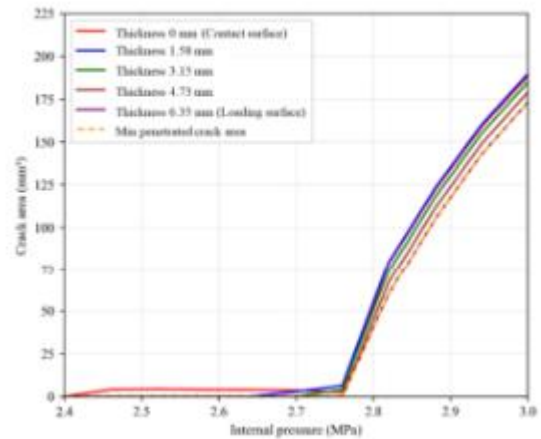


Fig. 5. Internal pressure-crack area relationship up to the pressure at which crack area reaches its maximum (~3.0 MPa)

3. Conclusions

This study characterized the fracture behavior of the APR1400 containment liner plate under ultimate internal pressure using a three-dimensional XFEM-based sector model, refining the crack-area evaluation to the pressure range in which the crack actually develops. The results show that the crack area remains negligible up to approximately 2.7–2.8 MPa, after which it grows sharply and reaches a maximum value of about 200 mm² near 3.0 MPa, corresponding to full through-thickness penetration of the liner near the embedded angle and channel components; beyond this pressure, the crack area no longer increases appreciably. Because the liner plate constitutes the primary leak-tight boundary of the containment, this pressure–crack area relationship provides a quantitative, local

complement to the global structural response data typically obtained from large-scale containment tests [1], and offers a basis for assessing how much margin remains between the design-basis pressure and the onset of a through-thickness leak path.

Because each XFEM analysis of this kind is computationally expensive, repeating it whenever a new case needs to be evaluated is impractical for broader applications such as probabilistic margin assessment. To address this, future work will use a convolutional neural network (CNN)[5] to predict the crack area, at each pressure increment directly from the corresponding two-dimensional stress and strain contour field generated within a single XFEM analysis. The crack initiation and maximum crack area pressures will then be identified from this predicted pressure-crack area curve. The network will be trained on images from the lower pressure increments and evaluated against the corresponding XFEM results on the held-out, higher pressure increments where the crack actually develops, to test whether it generalizes to previously unseen loading levels. This approach will subsequently be extended to multiple structural and material configurations to improve its generalization capability, following the same general direction as other recent applications of CNNs to nuclear engineering problems [6,7].

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] Hessheimer, M.F., Klammer, E.W., Lambert, L.D., Rightley, G.S., & Dameron, R.A., Overpressurization Test of a 1:4-Scale Prestressed Concrete Containment Vessel Model, NUREG/CR-6810, SAND2003-0840P, U.S. Nuclear Regulatory Commission / Sandia National Laboratories, 2003.
- [2] Kim, D.-Y., Choi, J., & Kwon, T.-H., Detailed Modeling of Containment Building Liner Plate for XFEM-based Crack Analysis under Ultimate Internal Pressure, Transactions of the Korean Nuclear Society Spring Meeting, Jeju, Korea, May 7-8, 2026.
- [3] Moës, N., Dolbow, J., & Belytschko, T., A finite element method for crack growth without remeshing, International Journal for Numerical Methods in Engineering, Vol. 46, No. 1, pp. 131-150, 1999.
- [4] Kostić, N., Čamagić, I., Sedmak, A., Jovanović, M., Burzić, Z., Golubović, T., et al., Fracture and Fatigue Crack Growth Behaviour of A516 Gr 60 Steel Welded Joints, Metals, Vol. 14, No. 12, 1447, 2024.
- [5] LeCun, Y., Bottou, L., Bengio, Y., & Haffner, P., Gradient-based learning applied to document recognition, Proceedings of the IEEE, Vol. 86, No. 11, pp. 2278-2324, 1998.
- [6] Cancemi, S.A., Ambrutis, A., Povilaitis, M., & Lo Frano, R., AI-Powered Convolutional Neural Network Surrogate Modeling for High-Speed Finite Element Analysis in the NPPs Fuel Performance Framework, Energies, Vol. 18, No. 10, 2557, 2025.

- [7] Ju, B.-S., Son, H.-Y., & Lee, J., Advanced Sobol sensitivity analysis of a 1:4-scale prestressed concrete containment vessel using an ANN-based surrogate model, Nuclear Engineering and Technology, Vol. 57, 103259, 2025.