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Detailed Modeling of Containment Building Liner Plate for XFEM-based Crack Analysis Under Ultimate Internal Pressure

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1. Introduction

The structural integrity of containment buildings is essential for ensuring nuclear power plant safety under internal pressure. The liner plate functions as the primary leak-tight barrier, directly subjected to internal pressure during accident scenarios and may experience significant tensile stress, particularly near geometric discontinuities.

Under ultimate internal pressure beyond design-basis levels, localized stress concentrations can lead to crack initiation and propagation in the liner plate. Evaluating this fracture behavior is therefore critical for assessing containment performance and leak-tightness margins.

Conventional finite element approaches require remeshing to simulate crack growth, which increases computational cost and may reduce numerical stability. The Extended Finite Element Method (XFEM)[1] overcomes this limitation by allowing cracks to develop independently of mesh topology.

While previous research has largely focused on global structural response or concrete cracking, detailed fracture assessment of the steel liner at a local scale remains limited. This study investigates the fracture behavior of a containment liner plate under ultimate internal pressure using an XFEM-based sector model, with emphasis on crack initiation, propagation, and area quantification.

2. Methods and Results

2.1 Local Sector Modeling of Containment building

The extended finite element method (XFEM) was adopted to simulate crack initiation and growth in the steel liner plate under internal pressure. XFEM enables discontinuities to develop independently of the mesh, allowing stable tracking of crack evolution without remeshing. Since the liner plate forms the continuous pressure boundary of the containment, crack activation was restricted to the liner plate. Other structural components were modeled to ensure realistic stress transfer but were not assigned crack criteria.

Crack initiation was defined using the maximum principal stress criterion, with the critical stress taken as the yield strength of the liner material to conservatively detect the onset of localized damage. Damage evolution followed an energy-based mixed-mode formulation with linear softening behavior[2][3]. To quantify crack development, crack surface data obtained from XFEM analysis were extracted at selected frames. A Python-based post-processing routine was developed to calculate the crack area at each pressure increment, enabling direct establishment of the internal pressure–crack area relationship.

2.2 Sector Model and Boundary Conditions

The detailed modeling corresponds to a local region of the APR1400 containment building. To reduce the computational load while maintaining structural representativeness, a three-dimensional annular sector model was constructed. The sector angle was set to 1 degree to maintain cylindrical symmetry along the circumference. Symmetry constraints were also applied to the top and bottom of the model to reflect free-field conditions and maintain consistency in displacement and stress distributions.

The material properties of the concrete and steel members were defined based on the values used in APR1400. The concrete was modeled as linear elastic in this analysis step, while the liner plate and anchorage members were assigned nonlinear material properties that match their respective mechanical characteristics.

The interface between the concrete and the steel liner plate was modeled using nodal-to-surface contact. A penalty formulation with a tangential friction coefficient of 0.4 was used to simulate shear transfer across the interface.

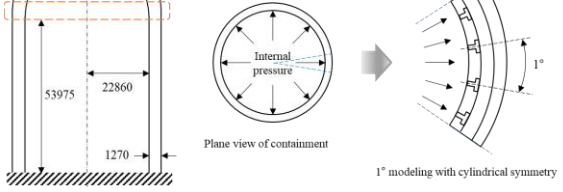

Fig. 1. APR1400 containment building and 1-degree cylindrical component

The inner surface of the liner plate was subjected to an ultimate pressure equal to 15 times the design pressure (Pd), which acts monotonically and uniformly. In the liner plate and anchorage areas, the mesh was refined to accurately capture stress concentration and crack initiation behavior.

2.3 Crack Response under Ultimate Internal Pressure

As internal pressure increased, stress redistribution in the liner plate progressed gradually. Von mises stress was not uniformly distributed along the liner surface but became localized near the anchorage region. This tendency is attributed to geometric discontinuity and local restraint effects associated with the anchorage configuration.

Crack initiation was observed in the liner plate element layer adjacent to the anchorage detail. At approximately the same pressure level, contact shear stress at the liner–concrete interface increased noticeably in the same region. The spatial correspondence between these responses indicates that crack initiation is influenced by the combined action of circumferential membrane stress and interface shear transfer.

Following crack initiation, the crack surface expanded steadily with further pressurization. Because concrete was modeled as linear elastic and crack activation was limited to the liner plate, the structural response remained stable within the investigated pressure range. No abrupt global instability was detected.

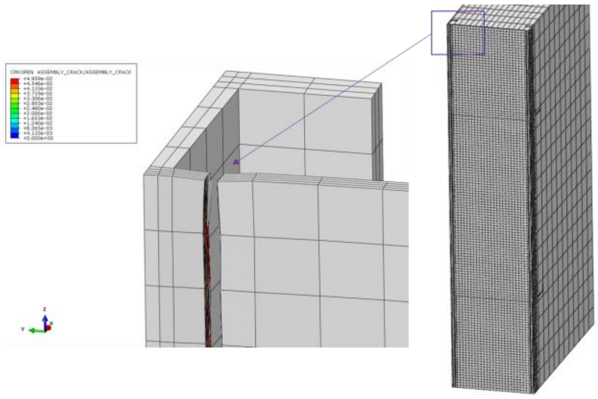

Fig. 2. Crack propagation of liner plate (Magnified 100×)

The results suggest that crack initiation is governed primarily by localized constraint effects rather than uniform hoop stress alone. These observations provide a quantitative basis for subsequent leakage assessment based on crack area evolution.

2.4 Crack Area Quantification

To quantify crack development in the liner plate, a dedicated post-processing procedure was established to compute crack surface area from XFEM analysis results. The crack surface generated by XFEM was extracted at selected analysis frames corresponding to each internal pressure increment.

Nodal coordinate data associated with the crack surface were obtained from the output database. These data represent discrete points defining the evolving discontinuity within the liner plate. Because XFEM does not directly provide crack area as an output variable, an additional computational step was required.

A Python-based algorithm was developed to process the extracted nodal coordinates and calculate the crack surface area. The procedure reconstructs the crack surface geometry from discrete nodal information and evaluates the projected surface area for each frame. This allowed consistent tracking of crack growth throughout the loading history.

The computed crack area values were then correlated with the corresponding internal pressure levels to establish a pressure–crack area relationship. This approach provides a quantitative measure of crack progression and enables direct evaluation of structural degradation in terms of surface discontinuity expansion. The proposed procedure offers a systematic framework for converting XFEM crack data into a measurable engineering parameter. It also provides a foundation for future estimation of leakage rates based on quantified crack area evolution.

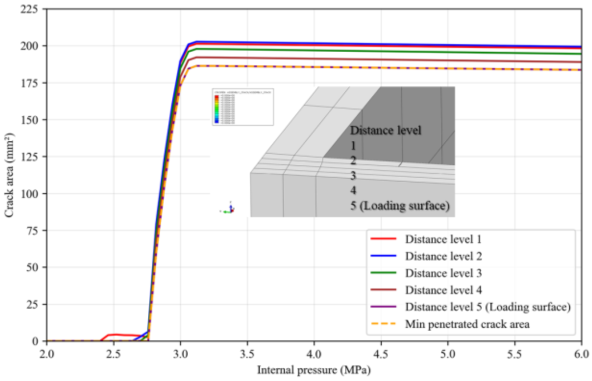

Fig. 3. Internal pressure-crack area relationship by distance level

3. Conclusions

This study examined the crack behavior of the APR1400 containment building liner plate under internal pressure using a three-dimensional sector finite element model with XFEM-based crack simulation.

Stress analysis indicated that the maximum principal stress was concentrated near the anchorage region rather than being uniformly distributed along the liner surface. Crack initiation occurred in the liner plate adjacent to the anchorage detail, highlighting the influence of local geometric discontinuity and interface-induced shear transfer.

Crack development was quantified in terms of surface area through a Python-based post-processing procedure. Crack initiation was observed only after the internal pressure exceeded a certain threshold level. Following initiation, the crack area increased with further pressurization and reached a peak within a limited pressure range. Beyond this stage, additional pressurization did not lead to significant expansion of the crack surface, and the crack area remained nearly constant.

This non-monotonic growth behavior suggests that crack propagation in the liner plate is governed by localized stress redistribution rather than continuous global instability. The observed stabilization of crack area indicates that, under the present modeling assumptions, damage progression becomes constrained after initial localization.

The proposed crack area–based evaluation framework provides a quantitative basis for assessing liner plate degradation and may be extended in future work to estimate leakage based on stabilized crack surface characteristics.

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