Evaluation of the Internal Pressure Capacity at Liner Failure in an Expanded Free-Field Region of the Small-scaled Prestressed Concrete Containment Vessel

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1. Introduction

Prestressed concrete containment vessel (PCCV) plays a critical role in ensuring the safety and integrity of nuclear power plants (NPPs) [1]. An understanding of the mechanical behavior and internal pressure capacity is vital for ensuring the safe operation of the NPPs [2]. In the Korean nuclear industry, it is still debatable which position of the liner can be used to determine liner failure. Hessheimer et al. [3] defined a free-field for determining liner failure as a reasonable distance away from discontinuities, such as equipment hatch (E/H), personal airlock (A/L), main steam (M/S), and feedwater (F/W) penetration, at a specific location with an azimuth of 135°. To determine liner failure at a leak in the domestic nuclear industry, the maximum principal strain of liner on a global finite element (FE) model with discontinuities has been chosen. Consequently, specific positions in the liner at the leak were predicted to be in the vicinity of E/H or A/L, corresponding to the maximum strain value of the liner. It is possible to introduce different internal pressure capacities at leak failure for PCCV models with ambiguous free-field positions for determining liner failure; thus, it is necessary to discuss acceptable free-field regions for PCCVs leak [2].

This paper summarizes a recently reported study [2] on determining the expanded free-field region at liner failure and comparing internal pressure capacity at different free-field positions in PCCV.

2. Numerical Analysis of 1/4-scaled PCCV

2.1 Material Constitutive Models

To accurately capture the nonlinear and inelastic behavior of the PCCV components, the concrete damaged plasticity (CDP) model was adopted to account for concrete behavior under stress [4]. Compression and tension of the concrete were represented by theoretical models suggested by Hognestad [5] and Izumo [6]. Additionally, an elastic-plastic model with isotropic hardening was considered to represent the behaviors of steel components, such as liner, rebar and tendon. Details of material properties for concrete, liner plate, rebar and tendon can be found in Cho et al. [2].

2.2 Details of FE Model

As shown in Fig. 1, the major components including concrete structure, liner, rebar and tendons of the 1/4-scaled PCCV were modeled in three dimensions using the guideline suggested by Hessheimer and Dameron [7]. Details of FE modeling can be found in Cho et al. [2]. For the FE modeling, continuum, 3D, 8-node (C3D8) for concrete, membrane, 3D, 4-node (M3D4) for liner and truss, 3D, 2-node (T3D2) for rebars and tendons were selected for this study [2].

As shown in Fig. 2(a), an internal pressure of up to 3.3 P_d (P_d = 0.39 MPa) was applied perpendicular to the surface of the liner. As depicted in Fig. 2(b), all degrees of freedom including node and element are constrained at the bottom of the basemat [2].

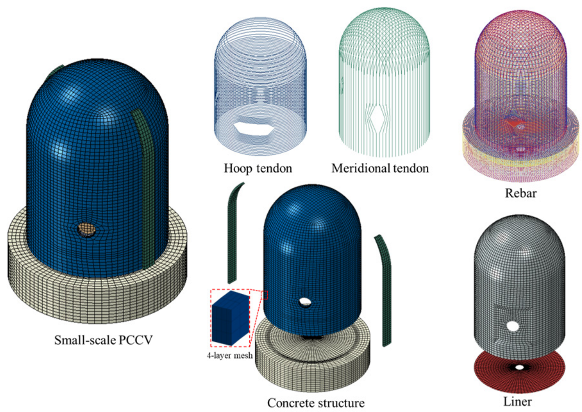
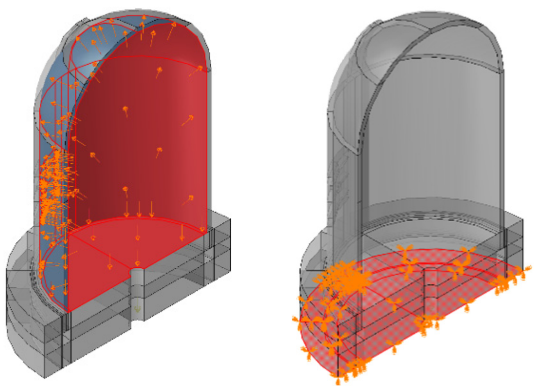


Fig. 1. Scheme of 1/4-scaled PCCV FE model [2].



(a) (b)

Fig. 2. Schemes of the pressure loading (a) and boundary conditions (b) [2]

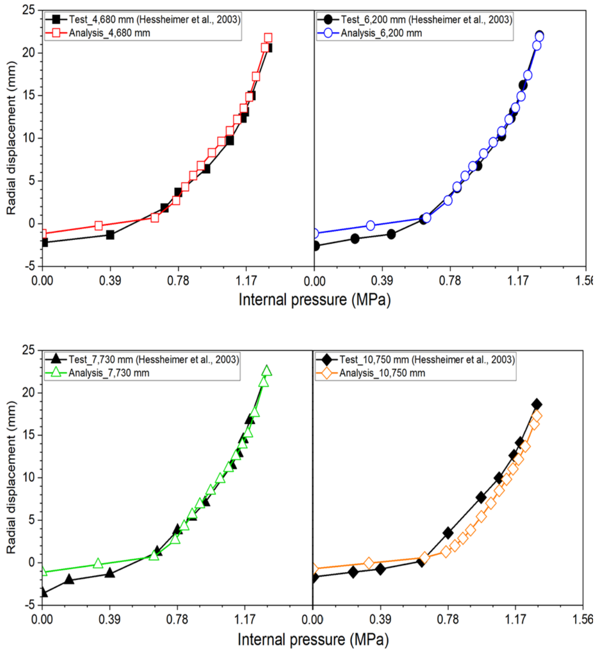


Fig. 3. Comparison of radial displacements between test data and numerical results [2]

To confirm the reliability of the developed FE model with a 300 mm element size, measured radial displacements at four different elevations from the test data [3] were compared with FE analysis results of the same azimuth of 135°, as shown in Fig. 3. The numerical results at three elevations (4,680, 6,200, and 7,730 mm) are generally consistent with those derived from the test data, although the analysis results at 10,750 mm exhibits little variance with a maximum disagreement of roughly 6.9% at 1.29 MPa (3.3 P_d). Due to the uniform distribution of prestress in tendon systems during FE analysis, a discrepancy in the radial displacements between experiment and analysis was observed [2].

3. Evaluation of Internal Pressure Capacity in Expanded Free-field regions at Leak

3.1 Determining Expanded Free-field

To address the ambiguity in defining liner failure positions, a practical approach is proposed to determine the expanded free-field region. This method involves two steps: (1) developing a virtual PCCV FE model without discontinuities and (2) careful examining the strain distribution in the liner to establish acceptable free-field ranges. By analyzing the virtual model, strain values ranging from approximately 0.31 % to 0.47 % were observed in the liner within an elevation range of 1,630 mm to 10,750 mm, as seen in Fig. 4. Then, the strain distribution along the cylindrical wall away from discontinuities was investigated. Based on this, an expanded free-field region was proposed with azimuths between 120° to 150° and 210° to 240°, along with elevations from 3,160 mm to 7,730 mm as illustrated in Fig. 5 [2].

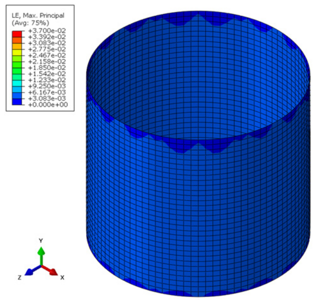


Fig. 4. Scheme of a virtual FE model without discontinuities [2]

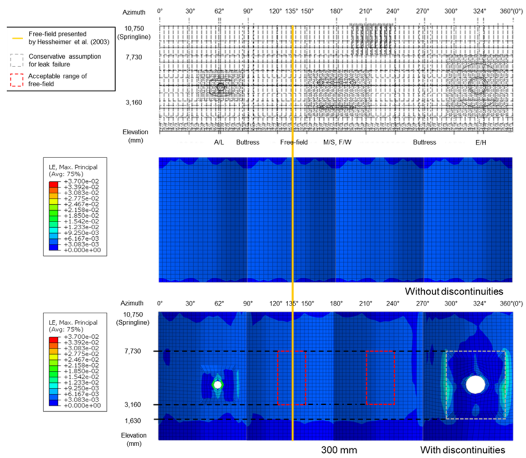
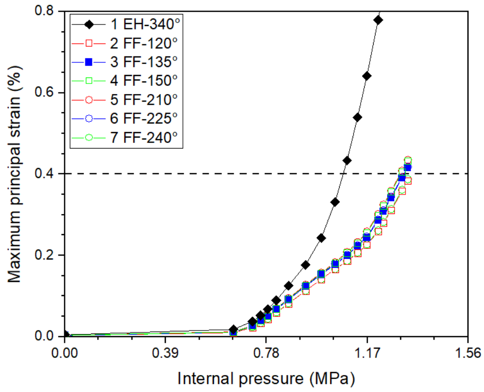


Fig. 5. Scheme of the expanded free-field region [2]

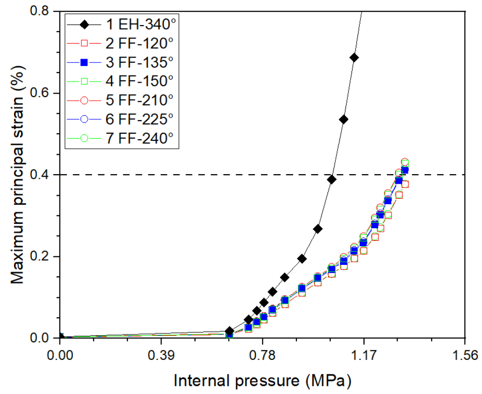
3.2 Predicted Internal Pressure Capacities

The internal pressure capacities of PCCV at different free-field positions were compared. At the classical free-field position (azimuth 135°), the internal pressure capacity at the leak differed by 14.66 % to 25.55 % compared to the vicinity of E/H at different elevations with 3,160, 4,680, 6,200 and 7,730 mm. At various free-field positions with three different azimuths (150°, 210°, 225°) in the expanded free-field region, the internal pressure capacity at liner failure showed considerable differences ranging from 13.27 % to 26.41 % compared to the adjacent E/H at different elevations with 3,160, 4,680, 6,200 and 7,730 mm. Since the maximum principal strain of the liner is less than the 0.4% failure criteria specified by RG 1.216 [8], internal pressure capabilities at leak are not included for all elevations at 120° and 240° within the expanded free-field region. Details on the comparison of the internal pressure capacities among different free-field positions can be found in Cho et al. [2].

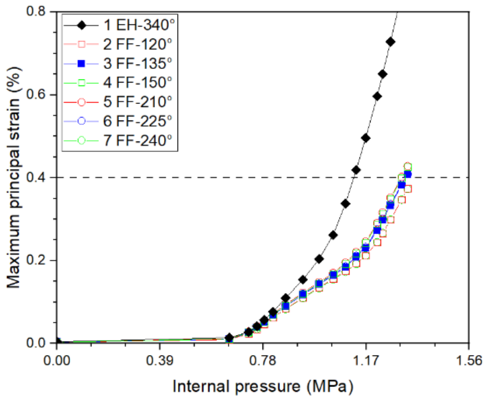
Comparisons of the maximum principal strain of the liner at the expanded free-field regions of 3,160, 4,680, 6,200 and 7,730 mm are shown in Fig. 6. Pressure capacities driven through the expanded free-field were evaluated to be higher than the E/H (azimuth 340°), where the largest strain values were captured because the strain concentration occurred due to its discontinuous geometry. These variations highlighted the importance of selecting the appropriate free-field location in determining the failure of the liner [2].



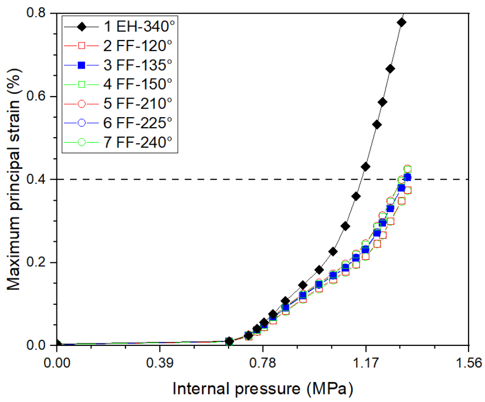
(a) Elevation: 3,160 mm



(b) Elevation: 4,680 mm



(c) Elevation: 6,200 mm



(d) Elevation: 7,730 mm

Fig. 6. Maximum principal strain of the liner at free-field region at various elevations [2]

4. Conclusion

This study provided a summary of determining the expanded free-field region at liner failure and comparing internal pressure capacity at different free-field positions in PCCV. To make accurate predictions of the structural response to internal pressure, advanced material constitutive models were used, and a comprehensive FE model was also developed. The proposed practical method for determining the expanded free-field region offered a systematic approach to address the ambiguity in defining liner failure positions. The results emphasized the need for careful consideration during the design, analysis, and evaluation of the containment structures in nuclear power plants by demonstrating the significant influence of free-field location on the internal pressure capacity of PCCV. Future research should further explore the applicability of the proposed methodology to different types of containments for a comprehensive understanding of the liner failure criteria.

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