

Parametric Sensitivity Analysis of Internal Pressure Capacity under Material Property Variations in Local FE Model for Equipment Hatch of 1:4 Scale PCCV

Ho-Young Son^a, Do-Yeon Lee^b, Yoon-Suk Chang^b, Sangwoo Lee^a, Yu-Gyeong Jung^a, Bu-Seog Ju^{a*}

^aDepartment of Civil Engineering, Kyung Hee University, 1732 Deogyong-daero, Yongin-si, Republic of Korea

^bDepartment of Nuclear Engineering, Kyung Hee University, 1732 Deogyong-daero, Yongin-si, Republic of Korea

*Corresponding author: bju2@khu.ac.kr

***Keywords :** Local FE Model, Equipment Hatch, Internal Pressure Capacity, Sensitivity Analysis

1. Introduction

The evaluation of internal pressure capacity of prestressed concrete containment vessels (PCCVs) has been a critical issue in nuclear safety since the Chernobyl and Three Mile Island nuclear power plant accidents. The U.S. Nuclear Regulatory Commission (NRC) Regulatory Guide (RG) 1.216 provides failure criteria for assessing the structural integrity of containment vessels under beyond-design-basis internal pressure loads and recommends finite element (FE) analysis-based evaluation of internal pressure capacity [1]. Accordingly, various experimental and analytical studies have been conducted to investigate the internal pressure capacity and failure mechanisms of PCCVs.

Most of the existing analytical studies have focused on evaluating the overall internal pressure behavior of containment vessels using global FE models. However, the overpressurization test of the 1:4 scale PCCV conducted at Sandia National Laboratories (SNL) revealed that functional failure was primarily caused by localized liner tearing around penetration areas [2]. Such liner tearing is attributed to the structural discontinuities of T-anchors and the frictional behavior between concrete and liner, which are difficult to accurately capture using global models. RG 1.216 also recommends that the internal pressure capacity of penetrations be evaluated using detailed local FE models.

Meanwhile, the internal pressure capacity of PCCVs can be significantly influenced by the material properties of structural components, such as the compressive strength of concrete, yield strength of reinforcing steel, and prestressing force of tendons. In actual structures, variability in material properties is inevitable, and systematically understanding the effects of such variability on the internal pressure capacity is essential for safety evaluation. Nevertheless, studies that analyze the sensitivity of internal pressure capacity to variations in material properties applied to local models of penetration areas remain insufficient.

Therefore, this study aims to analyze the sensitivity of internal pressure capacity to material property variations using the local FE model for the Equipment Hatch (EH) developed based on the 1:4 scale PCCV test conducted at SNL. First, the configuration and validation results of the local FE model are presented,

followed by a sensitivity analysis of internal pressure capacity with respect to the defined variation ranges of key material properties.

2. Local FE model for Equipment Hatch of 1:4 scale PCCV

2.1 Description of Local FE Model

In the 1:4 scale PCCV overpressurization test conducted at SNL, a total of 26 liner tears were reported, of which five occurred in the vicinity of the EH [2]. NUREG/CR-6810 identifies the geometric discontinuity of penetrations and local strain concentrations induced by T-anchors, stiffeners, and welds as the primary causes of liner tearing. Considering these experimental findings and structural characteristics, the present study developed a local FE model targeting the EH.

Since specific analysis guidelines for evaluating the internal pressure performance of PCCV penetrations using a local FE model have not been established, a three-dimensional local FE model was developed in this study by referring to the detailed design drawings of the 1:4 scale PCCV [2]. The height range of the model was set to 1,630–7,730 mm to encompass the locations where liner tearing was observed, and the azimuthal extent was configured to cover approximately 32° around the hatch center. As the overpressurization test indicated that liner tearing was caused by localized strain concentration near discontinuities and T-anchors, the T-anchors and stiffeners that bond the liner plate to the concrete were modeled in detail.

Element types were selected to appropriately represent the mechanical behavior of each structural component. Reduced-integration 8-node solid elements (C3D8R) were used for concrete, while reduced-integration 4-node shell elements (S4R) were employed for the liner to effectively capture curvature effects, bending, and shear deformation. Two-node truss elements (T3D2) were adopted for both reinforcing bars and tendons. The reinforcing bars were arranged in a double-layer configuration with vertical and horizontal orientations.

Frictional contact conditions were applied between the concrete and the liner to accurately simulate the local behavior of the liner. A friction coefficient of 0.35 was adopted based on previous experimental studies on

concrete-steel plate friction [3, 4]. The prestressing force of the tendons was applied using the *Predefined field option in ABAQUS. The boundary conditions of the local FE model were imposed using the *Submodeling technique in ABAQUS, which applies the displacement results obtained from the global FE model developed in a previous study [5]. The loading sequence consisted of the self-weight of the 1:4 scale PCCV in the first step, followed by a gradual application of internal pressure in the second step.

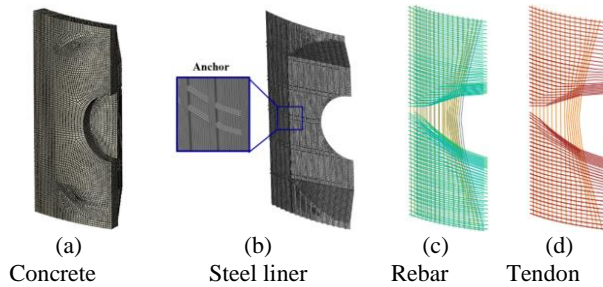


Fig. 1. Local FE model for Equipment Hatch

2.2 Validation

To establish the reliability of the local FE model, validation was performed by comparing the liner strains at locations where liner tearing was observed around the EH with the experimental results. Liner tearing in the EH was primarily observed near the left and right edges of the hatch, and the hoop-direction strains at these locations were selected for comparison.

A comparison between the experimental and FE analysis results showed that the overall trends of liner strain were similar in the internal pressure ranges of 0.0–0.6 MPa and above 1.2 MPa. However, some discrepancies were observed in the 0.6–1.2 MPa range. These differences are attributed to the 25–54% reduction in liner thickness at the tearing locations due to the post-weld grinding process, as well as structural variability including material variability of concrete and steel components and variations in tendon prestressing force [2].

Nevertheless, the FE analysis predicted higher strains than those observed in the experimental test, confirming that a conservative evaluation is achievable. The maximum strain error at the EH was approximately 2.65%, demonstrating that the analysis results are in close agreement with the experimental data. The discrepancies observed in certain internal pressure ranges are attributed to structural discontinuities arising from the welding process at liner connections and the grinding process for strain gauge attachment, along with associated material variability. Overall, the validity of the local FE model was successfully verified.

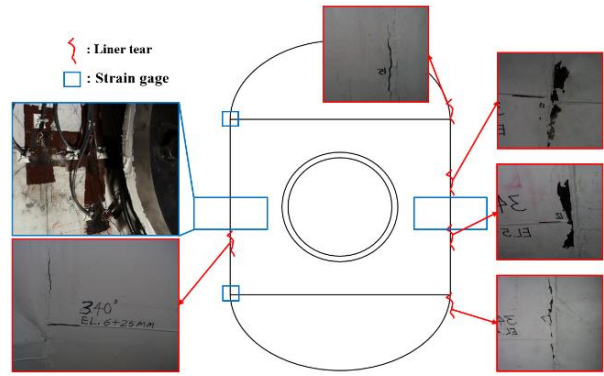


Fig. 2. Location of Liner Tearing in Equipment Hatch

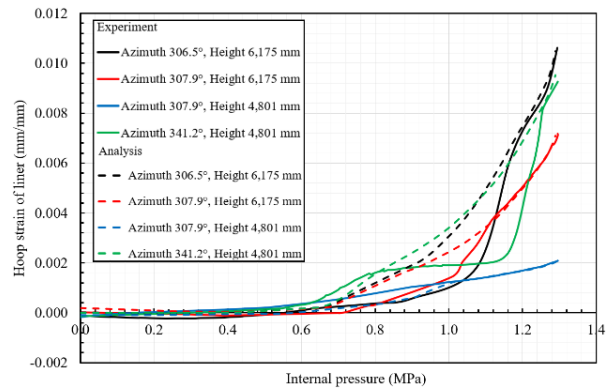


Fig. 3. Compare to Experimental Test and FE analysis in Equipment Hatch

3. Sensitivity Analysis for Material Properties Variation

3.1 Variation of Material Properties

The variability present in containment vessels can be broadly classified into structural and material variability, both of which can significantly affect the internal pressure capacity. Structural variability refers to construction tolerances and geometric deviations that arise during the construction process. Since nuclear containment vessels are built under stringent quality control, the influence of structural variability is considered to be minimal [6, 7]. Furthermore, the local FE model developed in this study incorporates detailed modeling of T-anchors, stiffeners, and boundary conditions such as the friction coefficient, and its reliability has been verified through comparison with experimental results. Accordingly, the structural variability of the model is judged to be low. Therefore, this study focused on material variability and performed a sensitivity analysis by applying the mean $\pm 3\sigma$ values of material properties to evaluate their effects on the internal pressure capacity.

The containment vessel consists of concrete, liner, T-anchors, rebar, and tendons, and exhibits nonlinear behavior as internal pressure increases. Therefore, the material properties of each structural component can have a considerable influence on the internal pressure

capacity. In addition, the SNL test results confirmed that the vertical and horizontal prestressing forces of tendons exhibit significant variability depending on the elevation and azimuth. In this study, the material properties of structural components and the prestressing force of tendons were selected as variability parameters.

The statistical characteristics of material variability are summarized in Table I and were determined based on the material test results from the overpressurization test and the statistical properties of PCCV material variability presented in NUREG/CR-6920[8].

Table I: Statistical Characteristic of Material Properties

Component	Property	Mean	COV
Concrete	Compressive Strength (MPa)	41.3	0.15
	Elastic Modulus Factor	1.0	0.077
	Tensile Strength Factor	1.0	0.196
Liner	Elastic Modulus (MPa)	200,000	0.06
	Yielding Strength Factor	1.0	0.07
	Ultimate Strength (MPa)	498.2	0.09
T-Anchor	Elastic Modulus (MPa)	200,000	0.06
	Yielding Strength Factor	1	0.07
	Ultimate Strength (MPa)	450	0.09
Rebar	Elastic Modulus (MPa)	183,333	0.06
	Yielding Strength Factor	1.0	0.07
	Ultimate Strength (MPa)	611.7	0.06
Tendon	Elastic Modulus (MPa)	200,000	0.06
	Yielding Strength Factor	1.0	0.07
	Ultimate Strength (MPa)	1876.1	0.09
	Prestressing Factor	1.0	0.03

3.2 Internal Pressure Capacity under Material Properties Variation

A sensitivity analysis was performed to evaluate the influence of material property variability on the internal pressure capacity of the containment vessel. Nonlinear FE analyses were conducted by applying material properties corresponding to the mean(μ) $\pm 3\sigma$ for each variability parameter, and the internal pressure capacity was evaluated using the strain response at the upper-right corner of the EH, where the maximum strain was observed.

Table 2 presents the internal pressure capacity based on variation in liner plate material properties. Increases in ultimate and yield strengths resulted in approximately 4.4% and 4.5% increases in internal pressure capacity, respectively, while changes in elastic modulus had a negligible effect.

Table 3 summarizes the sensitivity of internal pressure capacity to tendon material properties. The yield and ultimate strengths of tendons had minimal impact on the internal pressure capacity. However, the elastic modulus and prestressing force exhibited notable sensitivity, with increases of approximately 3.2% and 4.3%, respectively.

Table 4 shows the internal pressure capacity for variations in T-anchor material properties. Unlike other components, a decrease in the yield and ultimate strengths of T-anchors led to a slight increase in internal pressure capacity (approximately 1%). This is because increased anchor stiffness causes earlier yielding of the liner plate, inducing localized strain concentration at the T-anchor-to-liner junction.

Table 5 presents the effect of rebar material property variations on the internal pressure capacity. Reductions in yield strength, ultimate strength, and elastic modulus resulted in decreases of 1.9%, 1.7%, and 1.5%, respectively, indicating a moderate and relatively uniform level of influence.

Table 6 summarizes the results for concrete material property variations. Among all parameters considered, the tensile strength of concrete exhibited the highest sensitivity, with an increase of 11.3% at $+3\sigma$. This is attributed to the tension-dominated behavior of the containment vessel under internal pressure, where concrete cracking induces significant nonlinearity that amplifies the effect of tensile strength on the overall pressure capacity.

In summary, the tensile strength of concrete was identified as the most influential parameter, followed by the yield and ultimate strengths of the liner plate and the prestressing force of tendons.

Table II : Internal Pressure Capacity based on Variation in Concrete Material Properties

Property	Internal Pressure Capacity (MPa)			Relative Change (%)	
	-3 σ	μ	+3 σ	-3 σ	+3 σ
Compressive Strength(f_c)	0.9571	0.9711	0.9743	-1.4	0.3
Elastic Modulus(E_c)	0.9844	0.9711	0.9617	1.4	-1.0
Tensile Strength(f_t)	0.9688	0.9711	1.0807	-0.2	11.3

Table III : Internal Pressure Capacity based on Variation in Liner Material Properties

Property	Internal Pressure Capacity (MPa)			Relative Change (%)	
	-3 σ	μ	+3 σ	-3 σ	+3 σ
Elastic Modulus(E_L)	0.9735	0.9711	0.9698	0.2	-0.1
Yielding Strength($f_{y,L}$)	0.9364	0.9711	1.0146	-3.6	4.5
Ultimate Strength($f_{u,L}$)	0.9291	0.9711	1.0134	-4.3	4.4

Table IV : Internal Pressure Capacity based on Variation in T-Anchor Material Properties

Property	Internal Pressure Capacity (MPa)			Relative Change (%)	
	-3 σ	μ	+3 σ	-3 σ	+3 σ
Elastic Modulus(E_A)	0.9764	0.9711	0.9685	0.5	-0.3
Yielding Strength($f_{y,A}$)	0.9809	0.9711	0.9662	1.0	-0.5
Ultimate Strength($f_{u,A}$)	0.9814	0.9711	0.9648	1.1	-0.6

Table V : Internal Pressure Capacity based on Variation in Rebar Material Properties

Property	Internal Pressure Capacity (MPa)			Relative Change (%)	
	-3 σ	μ	+3 σ	-3 σ	+3 σ
Elastic Modulus(E_R)	0.9566	0.9711	0.9808	-1.5	1.0
Yielding Strength($f_{y,R}$)	0.9546	0.9711	0.9781	-1.7	1.0
Ultimate Strength($f_{y,R}$)	0.9530	0.9711	0.9777	-1.9	0.7

Table VI : Internal Pressure Capacity based on Variation in Tendon Material Properties

Property	Internal Pressure Capacity (MPa)			Relative Change (%)	
	-3 σ	μ	+3 σ	-3 σ	+3 σ
Elastic Modulus(E_T)	0.9410	0.9711	1.0022	-3.1	3.2
Yielding Strength($f_{y,T}$)	0.9711	0.9711	0.9711	0.0	0.0
Ultimate Strength($f_{u,T}$)	0.9711	0.9711	0.9711	0.0	0.0
Prestressing Force	0.9312	0.9711	1.0124	-4.1	4.3

4. Conclusions

This study performed a sensitivity analysis to evaluate the influence of material property variations on the internal pressure capacity of the Equipment Hatch (EH) in a 1:4 scale PCCV using a local FE model. The main findings are summarized as follows.

A three-dimensional local FE model for the EH was developed based on the detailed design drawings of the 1:4 scale PCCV test conducted at SNL. The model incorporated T-anchors, stiffeners, and frictional contact between the concrete and liner to accurately capture local behavior. The developed model was validated by comparing the hoop-direction liner strains at tearing locations with the experimental results, showing a maximum strain error of approximately 2.65% and confirming that the model provides conservative predictions.

The sensitivity analysis was conducted by varying the material properties of five structural components within the mean $\pm 3\sigma$ range. The tensile strength of concrete was identified as the most influential parameter, increasing the internal pressure capacity by 11.3% at +3 σ , due to the tension-dominated behavior of the containment vessel under internal pressure. The yield and ultimate strengths of the liner plate and the prestressing force of tendons were also found to be significant parameters, each contributing approximately 4.3–4.5% variation in internal pressure capacity.

These findings provide essential guidance for selecting key variability parameters in probabilistic internal pressure capacity evaluations of PCCV penetrations. Future research will utilize these results to perform a probabilistic fragility assessment incorporating the identified dominant material property variability.

REFERENCES

- [1] U.S. Nuclear Regulatory Commission, Containment Structural Integrity Evaluation for Internal Pressure Loadings above Design Basis Pressure, Regulatory Guide 1.216, 2010.
- [2] 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, U.S. Nuclear Regulatory Commission, 2003.
- [3] Q. Guo, Q. W. Chen, Y. Xing, Y. N. Xu, and Y. Zhu, Experimental Study of Friction Resistance between Steel and Concrete in Prefabricated Composite Beam with High-Strength Frictional Bolt, *Advances in Materials Science and Engineering*, Vol. 2020, 1292513, 2020.
- [4] B. G. Rabbat and H. G. Russell, Friction Coefficient of Steel on Concrete or Grout, *Journal of Structural Engineering*, Vol. 111, p. 505-515, 1985.
- [5] B. S. Ju and H. Y. Son, Enhanced Stochastic Approaches for 1:4 PCCV in Nuclear Power Plant: Uncertainty Quantification and Fragility Assessment, *International Journal of Energy Research*, Vol. 2024, 7770831, 2024.
- [6] Z. Zheng, A. Tian, X. Pan, D. Ji, and Y. Wang, The damage-based fragility analysis and probabilistic safety assessment of containment under internal pressure, *Reliability Engineering and System Safety*, Vol. 241, 109658, 2023.
- [7] T.K. Mandal, S. Ghosh, and N.N. Pujari, Seismic fragility analysis of a typical Indian PHWR containment: comparison of fragility models, *Structural Safety*, Vol. 58, p.11-19, 2016.
- [8] B. W. Spencer, J. P. Petti, and D. M. Kunsaman, Risk-informed assessment of degraded containment vessels, Technical Report No. NUREG/CR-6920, SNAD2006-3772P, SAND2006-2274P. U.S. Nuclear Regulatory Commission, Washington, DC, USA, 2000.