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Probabilistic Assessment of Internal Pressure Capacity of Prestressed Concrete Containment Building

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1. Introduction

The containment building in a nuclear power plant (NPP) serves as the final barrier to prevent the leakage of radioactive materials under severe accident conditions. This study aims to assess the internal pressure capacity of a prestressed concrete containment building, considering uncertainties in material properties and prestress loss.

2. Modeling of the containment building

2.1 Geometry of the containment building

The containment building investigated in this study is a prestressed concrete structure based on APR1400-type NPPs in Korea. The model includes major penetrations and three buttresses, as shown in Fig. 1. A liner plate is attached to the concrete containment wall, while rebars and tendons are embedded within the concrete.

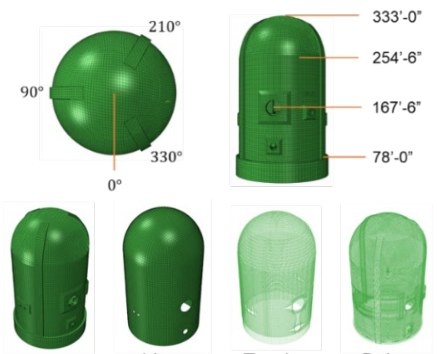

Fig. 1. 3D finite element model of containment building

2.2 Material models

The Concrete Damaged Plasticity (CDP) model in ABAQUS is used for the concrete material, while a bilinear model is applied to the steel components, including the liner plate, rebars, and tendons. The stress-strain relationships of the materials are shown in Fig. 2 and Fig. 3.

Table 1 presents the median strengths and logarithmic standard deviations β of materials applied in this model. The median strengths are referenced from the performance report of the US-APWR containment [1], which includes material properties similar to those used in APR1400-type NPPs, along with temperature effects. The uncertainties in material properties are determined based on field data acquired from nuclear power plants in Korea. Data from four plants were analyzed, and the maximum standard deviation for each parameter was conservatively selected.

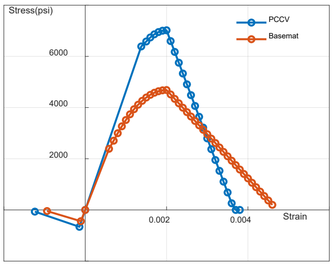

Fig. 2. Stress-strain relationship of basemat and prestressed concrete containment vessel(PCCV) concrete

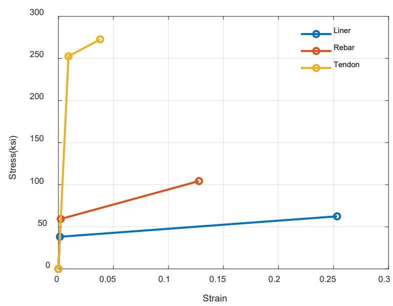

Fig. 3. Stress-strain relationship of steel components

Table 1: Median strengths and logarithmic standard deviation of materials

Material	Parameter	Median (MPa)	β	95% confidence (MPa)
Basemat Con'c	$f_{c,base}$	32.3	0.104	27.2
PCCV Con'c	$f_{c,PCCV}$	48.4	0.127	39.3
Rebar	$f_{y,rebar}$	409.0	0.071	363.9
	$f_{u,rebar}$	719.3	0.055	657.0
Liner	$f_{y,liner}$	263.2	0.037	247.6
	$f_{u,liner}$	430.6	0.036	405.8
Tendon	$f_{y,tendon}$	1740.6	0.015	1698.2
	$f_{u,tendon}$	1879.4	0.017	1827.5

2.3 Prestress loss

Initial prestress decreases due to both instantaneous and long-term factors. If test results related to prestress loss are available, the loss can be calculated following RG 1.35.1[2]. However, in case where experimental results are unavailable, multiple assumptions must be made. Thus, in this analysis, the design prestress is conservatively applied, as the actual prestress is assumed to be higher than the design value. The design prestress for an old plant in Korea is as shown in Table 2 [3].

Table 2: Design prestress [3]

Type of tendon	Design prestress (ksi)
Vertical tendons	$162.4(0.601f_{pu})$
Horizontal tendons of wall	$163.7(0.606f_{pu})$
Horizontal tendons of dome	$162.8(0.603f_{pu})$

Uncertainty in prestress loss is determined based on a literature review. Hahm et al. [4] suggested a logarithmic standard deviation β of 0.025 based on measurements from a prestressed test beam of Wolsung Unit 1. Gilbertson and Ahlborn [5] calculated β based on the variability of 17 input parameters affecting prestress loss, such as yield and ultimate strengths of tendons, jacking stress, unit weight and compressive strength of concrete, relative humidity, and other factors. The value of β was found to range from 0.036 to 0.119. The maximum value, 0.119, is applied in this study.

3. Assessment of internal pressure capacity

3.1 Failure criteria

RG 1.216 [6] provides a simplified method for determining the pressure capacity of cylindrical prestressed concrete containment building. The pressure capacity is estimated based on the following strain limits: (1) a total tensile average strain in tendons away from discontinuities (e.g., hoop tendons in a cylinder) of 0.8 percent, and (2) a global free-field strain for the other materials that contribute to resist the internal pressure (i.e., liner, if considered, and rebars) of 0.4 percent. These strain limits were applied in this study to determine the pressure capacity.

3.2 Analysis results

The strain of each structural member is determined through analysis. A point at a height of 212 ft in the containment, away from discontinuities, is considered a free-field location. Fig. 4 and Fig. 5 show the principal strain of liner plate and tendon at this point as internal pressure increases. The median case represents the analytical result with all median material properties and design prestress applied. The other cases show analysis results using the 95% confidence values of one property while keeping all other properties at their median values.

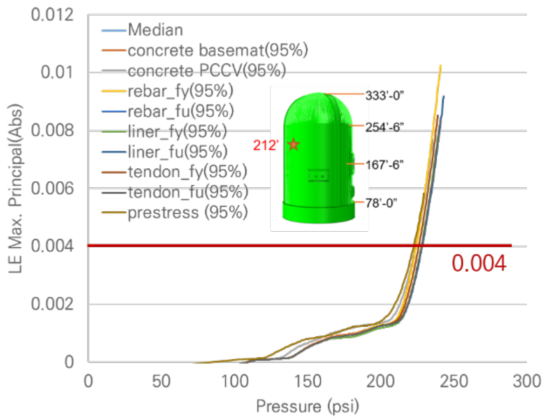

Fig. 4. Global free-field strain of liner plate

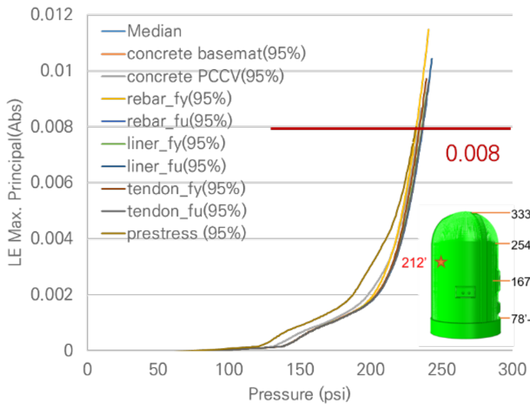

Fig. 5. Global free-field strain of tendons

3.3 Internal pressure capacity

The analysis results in Fig. 4 and Fig. 5 are used to determine the internal pressure capacity based on the failure criteria. The internal pressure capacities based on the strain limits of liner plate and tendons are shown in Table 3 and Table 4, respectively. For both criteria, prestress, compressive strength of PCCV concrete, and yield strength of rebars are the most influential parameters affecting internal pressure capacity.

Table 3: Internal pressure capacity based on the strain limit of liner plate of 0.4 percent

Case	Capacity (psi)
Median	228.21
Basemat Con'c (95%)	227.96
PCCV Con'c (95%)	223.83
rebar_fy (95%)	224.08
rebar_fu (95%)	228.08
liner_fy (95%)	227.70
liner_fu (95%)	228.21
tendon_fy (95%)	225.89
tendon_fu (95%)	228.00
Prestress (95%)	222.55

Table 4: Internal pressure capacity based on the strain limit of tendon of 0.8 percent

Case	Capacity (psi)
Median	236.82
Basemat Con'c (95%)	236.82
PCCV Con'c (95%)	233.73
rebar_fy (95%)	232.22
rebar_fu (95%)	236.67
liner_fy (95%)	236.12
liner_fu (95%)	236.77
tendon_fy (95%)	234.56
tendon_fu (95%)	236.56
Prestress (95%)	231.78

4. Conclusions

The internal pressure capacity of a prestressed concrete containment building was evaluated considering uncertainties in material properties and prestress loss. Some limitations exist, such as defining the logarithmic standard deviations of materials and prestress loss, the application of failure criteria, and the finite element modeling process itself. However, the results are still useful for assessing the internal pressure capacity of prestressed concrete containment buildings.

ACKNOWLEDGEMENTS

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