Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 19-20, 2022

Uncertainties Qualification of Prestressed Concrete Containment under Ultimate Pressure

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1. Introduction

With the Chernobyl nuclear power plant in Ukraine in 1986 and the Three Mile Island nuclear accident in the US in 1979, the safety of the nuclear power plant Reactor Containment Building(RCB) began to rise. After the 2011 Great East Japan Earthquake, the issue of the safety of the nuclear power plant structure for Beyond Design Basis Accident (BDBA) began to rise again. An experimental/ analytic study was performed to observe and understand the nonlinear behavior and failure mechanism by the ultimate pressure of the RCB at Sandia National Laboratory[1]. In the case of experimental research, it is practically difficult because economic/time costs are consumed. For estimation in Regulatory Guide(RG) 1.216, it is allowed to estimate the pressure capacity of the RCB through nonlinear finite element analysis. Among the materials used in the construction of RCB, concrete has various uncertainties compared to steel. In order to secure sufficient safety during the design life of a nuclear power plant, a behavioral analysis should be conducted considering the uncertainty of the material. In the study of Jin et al. (2019)[2], probabilistic safety evaluation by the internal pressure of the containment building was performed by statistical parameters of material properties recommended by the design codes for nuclear power plants in China and Europe. The study was conducted on CPR1000, and the material uncertainty of concrete and steel was extracted through latin hypercube sampling technique. Hahm et al. (2010)[3] developed a finite element model of a CANDU type containment building and performed an analysis of the fragility by internal pressure. In this study, the compressive strength of concrete and tensile strength of tendons were considered as uncertainties, and the vulnerability to leakage, breakage, and super-large breakage was evaluated. Hahm et al. (2014)[4] performed sensitivity analysis and fragility evaluation considering the material uncertainty of concrete and steel of PCCV type containment building. It was found that the decrease in tendon tension had a significant effect on pressure capacity. There are very few performance evaluation studies on the pressure capacity of RCB considering the uncertainty of material properties. Also, the performance evaluation using the verified finite element model is very small compared to the experimental research results. Therefore, this study developed and verified the finite element model based on the experimental study of Sandia National Laboratory. In addition, to analyze the behavior of RCB according to the sampling technique, concrete material uncertainties were sampled using Monte Carlo Simulation (MCS) and Latin Hypercube Sampling (LHS) techniques.

2. Finite Element Model of 1:4 Scale RCB

2.1 Description of 1:4 Scale RCB

Hessheimer et al. (2003)[1] performed a limit state test to analyze the nonlinear behavior and failure mechanism of the reduced-scale RCB against the input load under the Beyond Design Basis Accident condition. The target RCB is a Japanese PWR Ohi unit 3 and a Prestressed Concrete Containment Vessel (PCCV). The target containment building was manufactured on a 1:4 scale, which is the minimum scale that can produce a liner in a reduced scale. The height of the containment building is h=16,400mm, the radius R=5,375mm, the thickness t=325mm, and the thickness of the liner is t=1.6mm. Personnel Airlock and Equipment Hatch are located in Azimuth 62 and 324, respectively, and the overall shape is shown in Fig. equal to 1. The limit state test was performed by increasing the internal pressure through nitrogen gas injection. At 0.98 MPa, it was judged that the liner near the equipment hatch was damaged, and the experiment was terminated when it reached 1.295 MPa.

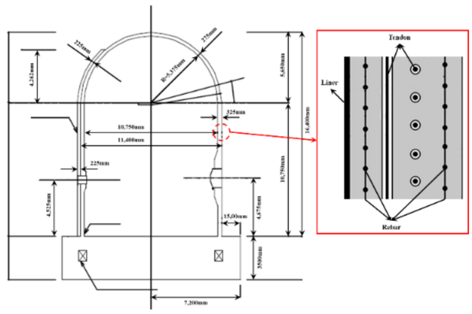
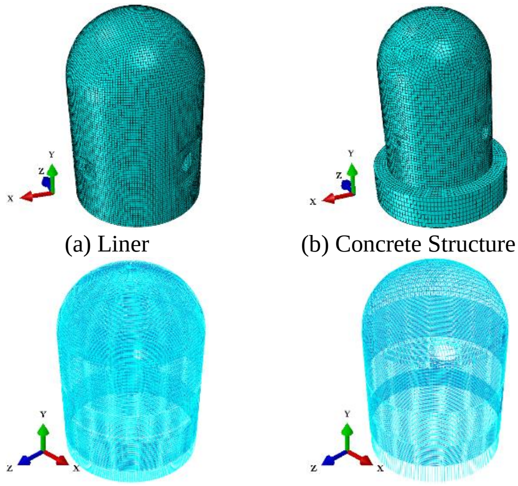


Fig. 1. Schematic Diagram of the Containment Building

2.2 FE Model of 1:4 Scale RCB

The finite element model of 1:4 Scale RCB was constructed with reference to the drawings of Hessheimer et al. (2003)[1]. In the limit state test, a finite element model was constructed considering the penetration part because the liner around the penetration part was damaged. The elements used for liner and concrete structure were 3D 8-node reduced integration membrane element (M3D8R) and 3D 8-node reduced integration solid element (C3D8R), respectively, and 3D 2-node truss element (T3D2) was used for rebar and tendon. The size of the element was determined to be 300 mm, and the number of elements and nodes used were 284,999 and 263,103, respectively. Fig. 2 shows the finite element model for each component of the 1:4 scale RCB.



(a) Liner (b) Concrete Structure

(c) Rebar (d) Tendon

Fig. 2. Finite Element Model of 1:4 Scale RCB

2.3 Material Properties

Material properties were prepared based on the results of the material test included in the appendix of Hessheimer et al. (2003)[1]. The Concrete Damaged Plasticity (CDP) model provided by the ABAQUS Platform[5] was applied to consider the nonlinearity of Concrete. The parameter used in the CDP model used the value provided by the ABAQUS user's manual[6]. The stress-stain relaxation of Concrete's uniaxial compression was proposed by Hognestad (1951)[7]. This model assumes linear elastic behavior up to 0.4fc and can then be expressed as Eq. (1) and (2).

$$\sigma_c = f_c\left[2\left(\frac{\varepsilon}{\varepsilon_c}\right) - \left(\frac{\varepsilon}{\varepsilon_c}\right)^2\right] \quad for\ \ \varepsilon \le \varepsilon_0 \qquad (1)$$

$$\sigma_c = f_c\left(1 - 0.15\frac{\varepsilon - \varepsilon_0}{\varepsilon_{cu} - \varepsilon_0}\right) \quad for\ \ \varepsilon \ge \varepsilon_0 \qquad (2)$$

Here, fc is the compressive strength of concrete, εcu is the maximum compressive strain of concrete, and ε0 is the strain of the maximum compressive strength of concrete. ε0 can be calculated as Eq. (3).

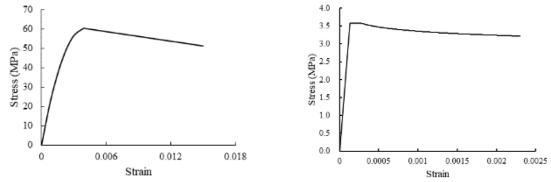
$$\varepsilon_0 = 1.8\frac{f_c}{E} \qquad (3)$$

The stress-strain relationship for the uniaxial tension of Concrete used the model proposed by Meakawa et al.[8] After the maximum tensile strength (ft), the strain increases from the crack strain εcr to 2εcr without reducing the stress, and then the stress decreases as shown in Eq. (4).

$$\sigma_t = f_t\left(\frac{\varepsilon_{cr}}{\varepsilon_t}\right)^c \qquad (4)$$

ft used 0.23(fc)2/3, and c used a tension stifling index of 0.05.

Elastic modulus E=27,200 MPa of Concrete and compression strength fc=60.3 MPa were used. Figure 3 shows the stress-strain relationship between uniaxial compression and tension.



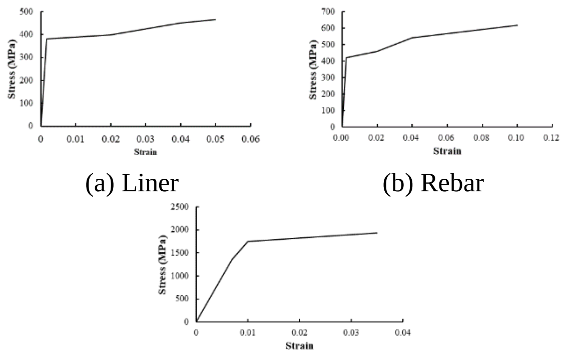
(a) Compression (b) Tension

Fig. 3. Stress-Strain Relation of Concrete Material

The material properties used for the liner, rebar, and tendon were assumed to be multi-linear, see Table I. It was assumed that the isotropic hardening method was used, and the stress-strain relation of each component is shown in Fig.4.

Table I: Material Properties of Steel[1]

Properties	Liner	Rebar	Tendon
Elastic Modulus (MPa)	224,000	183,000	195,000
Yield Stress (MPa)	380	420	1,350



(a) Liner (b) Rebar

(c) Tendon

Fig. 4. Stress-Strain Relation of Steel Material

2.4 Validation of FE Model

Dameron et al.[9]conducted a study on pretest analysis of 1:4 scale RCB. Here, the position where the global response by internal pressure of RCB can be observed was defined as azimuth 135°. Validation of the FE model compared the radial displacement of 6200 mm, which is the elevation including discontinuities at azimuth 135°, and Fig. 5 is shown. The initial displacement response is similar to the experimental and analysis results, but the stiffness of the analysis model after 0.59 MPa, which is predicted to yield concrete, is large. This is thought to be because it was assumed that the concrete, liner, rebar, and tendon were completely attached. At 1.295 MPa at the end of the experiment, the radial displacement was 24.16 mm, and the analysis result was 22.70 mm. However, since the tendency of the displacement response is similar and the error of maximum radial displacement is about 6%, the developed finite element model can similarly simulate the global response of 1:4 scale RCB.

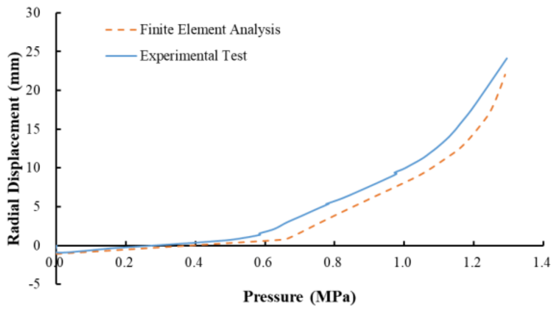


Fig. 5. Radial Displacement at Elevation 6200mm

3. Material Uncertainties in Concrete

3.1 Material Uncertainties Qualification

In the study of Alhanee et al. (2014)[10], in PCCV type containment building, structural damage occurs as the rebar and liner tendons yield sequentially after the concrete yields in tension when subjected to excessive pressure. Therefore, this study intends to analyze the behavior of the containment building by internal pressure considering the material uncertainties of concrete. In the study of Syed and Gupta (2015)[11], among the parameters used in the CDP model, dilation angle, compressive recovery factor, and tension recovery factor can be regarded as constants that cannot be directly evaluated through experiments. It was confirmed through loading simulation. Therefore, in this study, concrete material uncertainties were defined as elastic modulus and compressive strength. The statistical parameters of elastic modulus and compressive strength were determined as shown in Table II with reference to Hessheimer et al. (2003)[1].

Table II: Statistical Parameter of Concrete Material Uncertainties

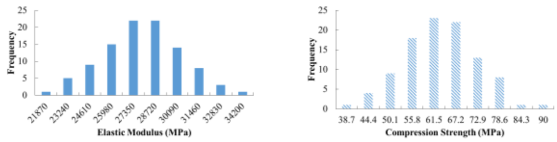
Uncertainties	Mean	Standard Deviation
Compressive Strength	60.3	9.588
Elastic Modulus	27,200	2,448

3.2 Material Uncertainties Sampling

Sampling using MCS is a method of extracting values approximating statistical parameters through random sampling. A certain level of accuracy can be reached only when a large number of iterations are performed.

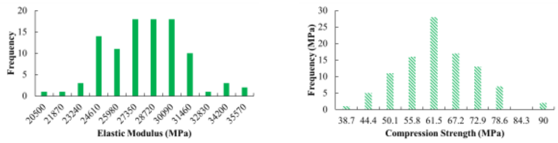
LHS is a method of extracting n parameters so that they do not overlap each other by dividing the probability distribution section into n when extracting each parameter and extracting one parameter from each section.

In this study, 100 concrete material uncertainties were sampled using different sampling techniques. Compression using Eq. (1)-(3), tension using Eq. (4) was create a stress-strain relation.



(a) Elastic Modulus (b) Compression Strength

Fig. 6. Concrete Material Uncertainties Sampling using LHS



(a) Elastic Modulus (b) Compression Strength

Fig. 7. Concrete Material Uncertainties Sampling using MCS

4. Result

Fig. 8 shows the comparison of radial displacement at an elevation of 6200 mm of azimuth 135°. When uncertainties were sampled through MCS, the mean was 19.64mm and the standard deviation was 2.60mm. When sampling through LHS, mean was 19.16mm and standard deviation was 2.38mm. The range of MCS-based radial displacement was found to be wider. This is because the elastic modulus and compressive strength were sampled in a relatively wide range.

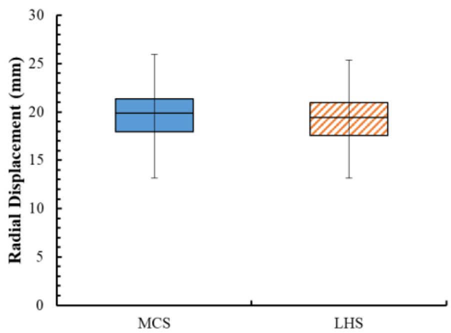


Fig. 8. Distribution of Radial Displacement at Elevation 6200mm.

5. Conclusion

This study analyzed the behavior of 1:4 scale RCB by ultimate pressure according to concrete material uncertainties. The difference in radial displacement according to the sampling technique was analyzed. Hessheimer et al.[1] developed a finite element model of RCB and verified the developed model by comparing it with the experimental results. When radial displacement was compared at elevation 6200mm of azimuth 135°, the overall behavior was similar, and the maximum displacement showed an error of about 6%, so it is thought that the developed model can well simulate the overall behavior of RCB. Material uncertainties were sampled using the LHS and MCS techniques, and the LHS technique showed a relatively even distribution. Comparing the radial displacements for 100 material uncertainties, it was found that the MCS technique showed relatively large standard deviation and range. Through this, it is judged that the sampling technique should be appropriately selected when analyzing the pressure capacity of the RCB considering material uncertainties. It is necessary to compare radial displacement at different azimuths and elevations in future studies.

ACKNOWLEDGMENTS

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. 2106034).

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