A Comparative Study on Ultimate Pressure Capacity by Containment Structure Type

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1. Introduction

Containment structure in a nuclear power plant (NPP) serves as a final barrier that prevents the release of radioactive materials, highlighting the necessity of maintaining its integrity under severe accident condition. Thus, experimental and analytical studies have been conducted to investigate the ultimate pressure capacity (UPC) of the structure under elevated temperature and internal pressure [1, 2]. Most of these studies have focused on concrete structures, which are commonly adopted in large NPPs. However, the steel containment vessel (SCV) has been adopted with the recent development of small modular reactors. Since the structure and material characteristics have changed from the conventional one, it is necessary to quantify the difference in the UPCs between concrete and steel structures to prepare for future designs.

In this study, finite element (FE) analyses for the SCV and 1/4 scaled prestressed concrete containment vessel (PCCV) were performed. The structural behaviors under internal pressure and saturated steam (SS) condition were analyzed. Finally, the UPC values of both cases were normalized and compared.

2. Numerical analysis of SCV and 1/4 scaled PCCV

2.1 Material Properties

In the SCV model, the materials were selected as SA-533 Type B, Class 2 for the upper section and SA-965 Type FXM-19 for the lower section. True stress-strain curve was calculated by using the equations provided in ASME Code Sec. VIII [3].

In the PCCV model, the concrete damaged plasticity (CDP) model was adopted to account for nonlinearity of the concrete [4]. Material parameters and properties in the model were selected from the previous study [1]. The isotropic elasto-plastic properties were used for the steel components of the tendons, rebars, and liner [1].

2.2 Details of FE Models

The constructed FE models are shown in Fig. 1. The penetrations and internal structures of the SCV were excluded except for the steam generator (SG) inspection flange. Furthermore, the CV ledge was incorporated as a vertical support for the internal structures. In the case of PCCV model, equipment hatch and air lock were considered as penetrations. In addition, the concrete contains 90 horizontal tendons, 108 vertical tendons, and two layers of rebars. Prestressing was applied in both the hoop and meridional directions of the containment structure.

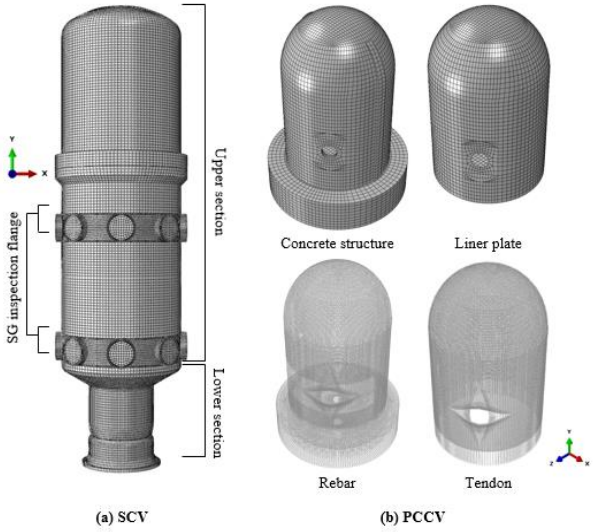

Fig. 1. Finite element models

Gravity and internal pressure were applied to the whole structure and inner surface, respectively. Every node of the bottom surface was fixed. Finally, to investigate combined effect of internal pressure and elevated temperature, SS condition was applied. Temperature and internal pressure history under the condition is depicted in Fig. 2.

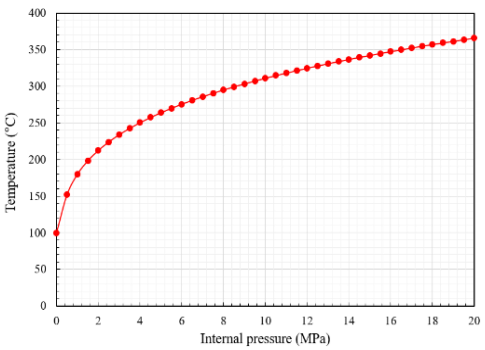

Fig. 2. SS condition

3. Analysis results

Fig. 3 shows the distribution of maximum principal strain. The maximum value occurred at the SG inspection flange in the SCV and at the equipment hatch and air lock in the PCCV. Both cases seem to be caused by the discontinuity effect.

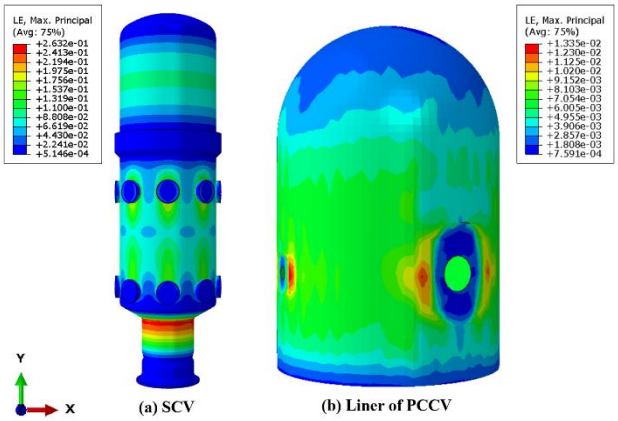

Fig. 3. FE analysis results

The regulatory guides in the Republic of Korea and the United States suggests that UPC should be evaluated away from discontinuities [5, 6]. In addition, the failure criteria have been proposed as 1.5% membrane strain for the SCV and 0.4% global strain in the liner for the PCCV. Thus, UPC evaluations were performed based on these failure criteria, as shown in Fig. 4. Then, the global strain was converted to a radial displacement, following Eq. (1).

$$\varepsilon_g = 0.4\% = \frac{\Delta r}{R} \quad (1)$$

where, ε_g is the global strain, Δr is the radial displacement and R is the radius of the PCCV.

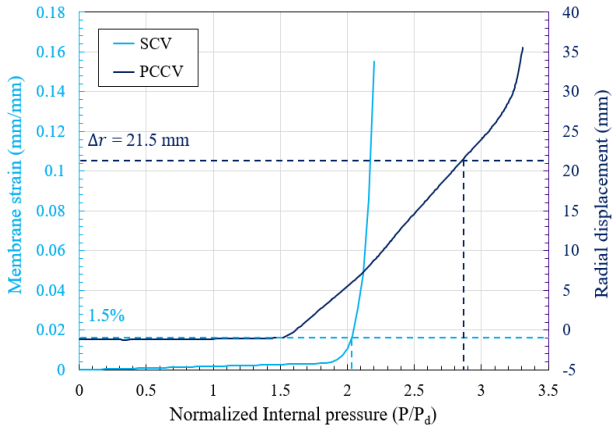

Fig. 4. Comparison of results

For direct comparison of the models, the UPCs were normalized by dividing with the design pressure (P_d) of each structure as summarized in Table 1. As a result, it was confirmed that the PCCV is approximately 1.41 times larger than the SCV. These results appear to be due to the variations and material characteristics.

Table 1: Summary of comparison results

	SCV* (P/P_d)	PCCV** (P/P_d)	Difference (%)
UPC	2.03	2.87	34.29%

* P_d of SCV: 5 MPa
** P_d of PCCV: 0.39 MPa

4. Conclusions

In this study, UPC evaluation was conducted for the SCV and 1/4 scaled PCCV using corresponding failure criteria. The results were analyzed and compared with the normalized values. The conclusions are as follows:

(1) Under the internal pressure and SS condition, the structural behaviors of models were analyzed. The vulnerable area is the SG inspection flange for the SCV and the equipment hatch for the PCCV.
(2) The generalized UPC of the PCCV was found to be 1.41 times larger than the SCV due to differences in the structure and material characteristics.
(3) These results can provide valuable insights for the currently developing future design of NPPs.

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