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Structural behaviour of 1:4 scale PCCV under high temperature and pressure with concrete postulated voids

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1. Introduction

The safety of containment buildings subjected to internal pressure due to accidents at some nuclear power plants has become an issue. As a result, experimental tests were conducted on the internal pressure capacity and failure mechanism of prestressed concrete containment vessels (PCCVs) under overpressure conditions[1]. In addition to experimental tests, studies were conducted on the evaluation of internal pressure capacity for functional and structural failures using FE models[2-4]. In addition, a probabilistic method-based fragility analysis was conducted considering material and structural uncertainties[5-7].

The PCCV consists of a concrete structure, steel liner, rebar, and tendon, and is reinforced with a T-type anchor to prevent the attachment of the steel liner and local buckling. Due to the closely spaced rebar and tendon, voids may occur in the corners of the connection of the T-type anchor where concrete is not filled. Oxygen and moisture remaining in the concrete voids can cause corrosion of the steel liner. In addition, in the event of a major accident, deformation can be concentrated on the steel liner located in the concrete void, which can cause functional failure at a relatively low internal pressure level. Not only PCCV, but also voids in most concrete structures can reduce structural performance. Since voids inside concrete cannot be inspected with the vision, various methods for detecting voids have been studied. However, research on the effects of concrete void on the internal pressure capacity of PCCV is very limited. Woo et al.[8] studied the structural integrity of containment buildings under internal pressure, taking into account concrete void. Response surface regression analysis was performed to develop an equation for predicting the reduction in internal pressure capacity due to concrete void, and probabilistic fragility analysis was performed.

Therefore, this study investigated the structural behaviour under the internal pressure of a 1:4 scale PCCV according to the postulated void in concrete.

2. FE Model of 1:4 scale PCCV

2.1. FE model

This study investigated the structural behavior of concrete considering the postulated void using the FE model developed based on the experimental test of the 1:4 scale PCCV performed at SNL[9]. The FE model of the 1:4 scale PCCV consists of a concrete structure, a steel liner, rebar, and tendon, as shown in Fig. 1. Concrete structure and steel liner were made using C3D8R and M3D4. Rebar and tendon were made using T3D2. Details of the material constitutive model, loading and boundary conditions were presented in previous research[9].

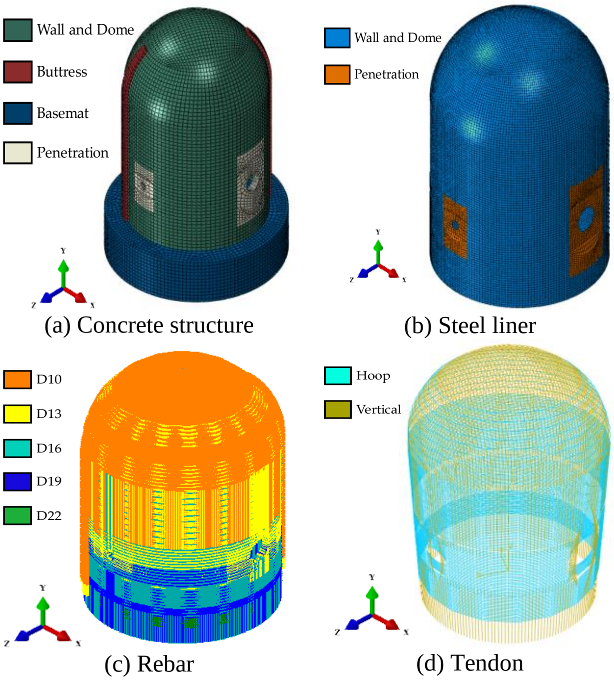


Fig. 1. FE model of 1:4 scale PCCV

2.2. Concrete void

In the study by Woo et al.[8], the concrete void was assumed to be the same as the axial consumption rate of the 1:4 scale PCCV, referring to the void that occurred in the main steam pipe sleeve of the PCCV operating in Korea. In the previous studies, the concrete void was determined as a wedge and rectangular type in consideration of the geometric shape of the occurrence case, and it was assumed to be located in the equipment hatch and free-field by recognizing the formation process of the concrete void. The research results showed that the rectangular type of concrete void had a greater impact on the reduction of internal pressure capacity than the wedge type, and that the concrete void that occurred in the equipment hatch was more fatal. This study assumed the most fatal concrete void scenario to clearly observe the recovery of internal pressure due to the filling of mortar in the concrete void. Therefore, it was assumed that the concrete void occurred in the rectangular type of equipment hatch. In addition, the geometric parameters in Fig. 2 were selected to observe the structural behaviour of a 1:4 scale PCCV according to changes in the volume of the concrete void, and are summarised in Table I.

For the case study according to the size, the thickness, width, and height of Fig. 2 were considered as geometric parameters and the structural behavior was investigated accordingly. Table 1 summarizes the geometric parameters for each case, and case 1 is the control group and the concrete postulated void in Woo et al.'s[8] study.

Table I: Geometrical parameter of postulated void

Case No.	Thickness (mm)	Width (mm)	Height (mm)	Volume (m^3)
1	420	300	260	0.0452
2	535	300	260	0.0542
3	310	300	260	0.0366
4	420	402	260	0.0542
5	420	203	260	0.0366
6	420	300	311	0.0542
7	420	300	210	0.0365

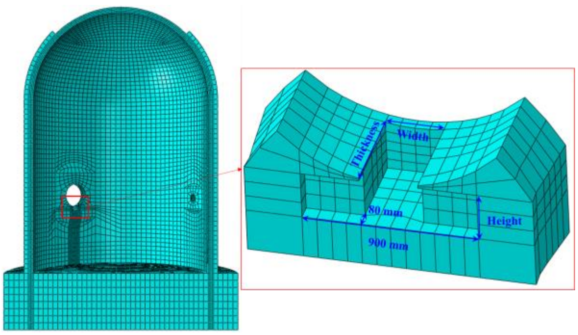


Fig. 2. Geometrical properties for postulated void

3. FE Analysis of 1:4 scale PCCV with Concrete Postulated Void under

3.1. Heat Transfer Analysis

In the event of a severe accident, the PCCV may experience an increase in temperature as well as an increase in internal pressure due to steam. The thermal expansion of components due to temperature increase can result in lower internal pressure capacity than when only internal pressure is applied [10]. Therefore, this study considered the saturated steam condition(SSC) assumed in previous studies to evaluate the structural behavior of a 1:4 scale PCCV according to concrete voids under a combination of temperature and internal pressure [11]. SSC assumes that the internal pressure and temperature increase monotonically due to saturated steam, as shown in Fig. 3. The pressurization rate of the internal pressure is about 0.034 MPa/min, and the maximum temperature increases to 200℃. In this study, a heat transfer analysis was performed to investigate the behavior of a 1:4 scale PCCV subjected to thermal loads and internal pressure. To perform the heat transfer analysis, the elements applied to concrete spheres and steel components were changed to those dedicated to heat transfer analysis, and the strength reduction according to the temperature load was applied as shown in Fig. 3, referring to the previous study[11]. Fig. 4 shows the temperature distribution of a 1:4 scale PCCV.

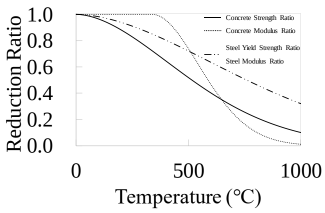


Fig. 3. Strength reduction ratio by temperature

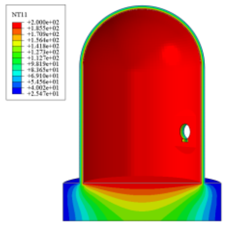


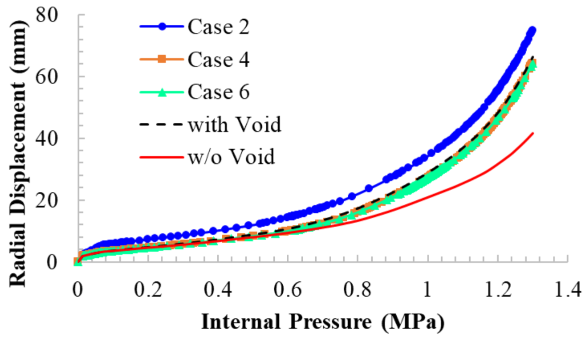
Fig. 4. Temperature contour

3.2. Structural Behavior under High Temperature and Internal Pressure

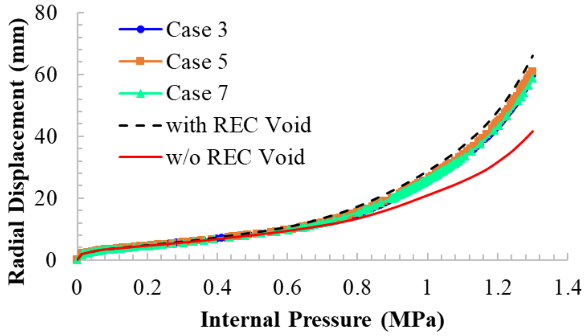
Fig. 5(a) compares the radial displacement-internal pressure relationship for the increase in the postulated void volume. In Case 1 (with void), the maximum radial displacement was calculated to be 66.19 mm, which is 58.7% higher than without (w/o) void. The radial displacement of case 2, in which the thickness was reduced in the same volume of void, was larger than that of cases 4 and 6, which were calculated similarly to case 1. In other words, the change in thickness in the same volume has a significant impact on the radial displacement.

Fig. 5 (b) compares the results of the case where the volume of the postulated void is reduced. The smallest radial displacement was calculated as 58.75 mm in case 3, where the thickness was increased compared to case 1, as in the case of increasing volume. The displacement in case 5 and 7 was calculated as 59.90 mm and 60.21 mm, respectively.

The internal pressure capacity was evaluated according to the criteria for functional failure of PCCV presented in the Regulatory Guide 1.216[12]. In Without void, the internal pressure capacity was evaluated as 0.971 MPa. The internal pressure capacity of Case 1 was 0.891 MPa, which was about 8.2% lower than Without void. The largest decrease in internal pressure capacity was observed in Case 2, which was about 0.826 MPa.



(a) Increase of postulated void volume



(a) decrease of postulated void volume

Fig. 5. Radial displacement-Internal pressure relation for postulated void volume

4. Conclusion

This study investigated the structural behavior of PCCV according to the concrete postulated void. The saturated steam condition (SSC) was applied and the structural behavior and internal pressure capacity according to the geometrical parameters of the void were compared. The geometrical parameters are thickness, width, and height, and changes in the geometrical parameters were applied to the increase and decrease of the volume. As a result, the radial displacement was greatly affected by the increase and decrease of the thickness of the postulated void. In addition, the internal pressure capacity in the case of reduced thickness decreased by about 15% compared to without void.

The concrete void in the PCCV is reinforced with mortar as soon as it is discovered in the safety inspection during operation. Therefore, it is necessary to evaluate the recovery of the internal pressure of the PCCV according to the mortar reinforcement of the concrete void. In addition, it is necessary to evaluate not only the evaluation according to the radial displacement but also the strain of the liner.

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