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A Proposal of the Ultimate Pressure Capacity Evaluation Method of Containment Buildings through a State-of-the-Art Review

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1. Introduction

Nuclear power plants have several safety systems to prevent leakage of radioactive material during severe accidents. Containment building acts as the final shielding barrier for radioactive material leakage in the event of a severe accident, therefore realistic ultimate pressure capacity assessments of containment buildings are performed in a varied approach.

Different types of containment buildings exist depending on the type of reactor and power generation system. In Korea, pressurized containment buildings are mainly used, consisting of concrete walls with reinforcement, tendons for pre-stressing loads, and steel liners. Because containment buildings are structurally complex systems, and the loads applied to them in the event of a severe accident are of such a magnitude that the nonlinearity of the materials must be considered, safety assessments are challenging.

In this study, reviewed the report and papers related to the ultimate pressure performance evaluation of containment buildings, organized them by type, and analyzed the advantages and disadvantages of each method. Based on this, proposed a reasonable method to evaluate the ultimate pressure capacity of containment buildings.

2. Ultimate Pressure Capacity Evaluation Methods

The most reliable way to verify the ultimate pressure performance of a containment building is to apply ultimate pressure loads to the actual structure. However, this method is very impractical, so a scale model of the containment building or a partially constructed structure is used to evaluate the ultimate pressure capacity. Experimental methods are also limited by practical constraints that prevent a large number of experiments from being conducted, and analytical methods are used in parallel to compensate for this.

2.1. Experimental Methods

There are three main types of containment structures/buildings: containment structures composed entirely of steel, containment buildings composed primarily of reinforced concrete, and containment buildings composed of prestressed reinforced concrete.

Several laboratories around the world have performed scale model experiments on various containment structures/buildings [1], which are summarized in Table 1.

Table I: Ultimate Pressure Capacity Evaluation of a Containment Building Scale Model

Type	Test Model	Scale
Steel Containment	SNL SC0	1:32
	SNL SC1	1:32
	SNL SC2	1:32
	SNL SC3	1:32
	SNL 1:8	1:8
	NUPEC/SNL SCV	1:10 geom. 1:4 thick.
Reinforced Concrete Containment	SNL RCCV	1:6
	CTL Spec. 2.5	Full
	CTL Spec. 2.4	Full
	CTL Spec. 3.2	Full
	CTL Spec. 2.2	Full
	CTL Spec. 3.3	Full
Prestressed Concrete Containment	Indian Model	1:12
	Polish Model	1:10
	Canadian Model	1:14
	Sizewell-B (CEGB)	1:10
	EPR Model (Civaux Test)	-
	NUPEC/NRC PCCV (SNL)	1:4

While these scale model experiments can be used to indirectly evaluate the ultimate pressure capacity of real structures, they also provide a reliable analytical methodology based on the experimental results. Experimental evaluations provide the most accurate results, but they are limited in their ability to reflect all of the various conditions under which a structure is subject to change during use. Therefore, an analytical method based on experimental results is used to evaluate the ultimate pressure capacity of containment buildings under various conditions.

2.2. Analytical Methods

2.2.1. Deterministic methods

In the past, finite element analysis was performed by developing a relatively simple analysis model, but with the development of finite element analysis techniques and computer hardware, finite element analysis is gradually being performed by developing realistic and complex analysis models.

The two-dimensional axisymmetric model is simple to develop and has good accuracy. However, there are limitations such as not being able to consider the unsymmetrical shape of the structure and not being able to simulate various failure modes [2].

The three-dimensional model can be divided into two methods: detailed modeling of tendons and reinforcement shapes and simple modeling with shell elements. The method using shell elements has the advantages of relatively easy modeling and short analysis time [3]. In particular, it is known that there is no significant difference in the analysis results for structures with very high reinforcement ratio such as containment buildings. In the case of a detailed model, it takes a lot of time to build the analysis model and convergence is often not secured depending on the analysis technique. However, it is possible to analyze various failure modes and analyze the response at localized locations. Most analytical evaluation methods have limitations in that they do not properly consider the uncertainty of the analytical model and the variability of material properties. In addition, they do not properly consider the current state characteristics of the target structure [4].

2.2.2. Probabilistic methods

In recent years, research has been performed in this field in response to the increasing demand for probabilistic stability assessment considering uncertainty factors. Existing studies applying probabilistic methods have limitations in that they do not reflect the current state by applying design-state material properties or rely on expert judgment in selecting sensitivity factors. In addition, conventional ultimate pressure vulnerability assessments have used the method of defining the probability distribution characteristics of the response by first assuming and then overlapping the uncertainties in the material and structural properties, i.e., the probability distribution characteristics, to estimate the uncertainty characteristics of the response. However, this method cannot account for the effect of individual material variable uncertainties on the variability of the response, which can lead to inaccurate results.

In addition, since the method of applying a monotonically increasing load or a load increase pattern based on a predetermined accident scenario was used to consider the pressure load, the evaluation of the ultimate pressure capacity under various load patterns is insufficient [5].

3. Proposal of the Method

The most accurate way to evaluate the ultimate pressure capacity of a containment building is to conduct a few physical experiments under various conditions, but this is not possible in practice. Therefore, it is recommended to evaluate the ultimate pressure capacity of a containment building through a finite element analysis that can be easily applied to various conditions.

When building a finite element analysis model, it is necessary to build a probabilistic analysis model that considers uncertainty factors. At this time, the uncertainty of each material variable should be considered independently. For this purpose, it is desirable to perform sensitivity analysis for each material variable to select representative factors and set the variation range of material properties. In addition, it is recommended to perform ultimate pressure analysis with various load combinations to consider the effects of various accident scenarios. The procedure for performing the analysis is shown in diagram in Figure 1.

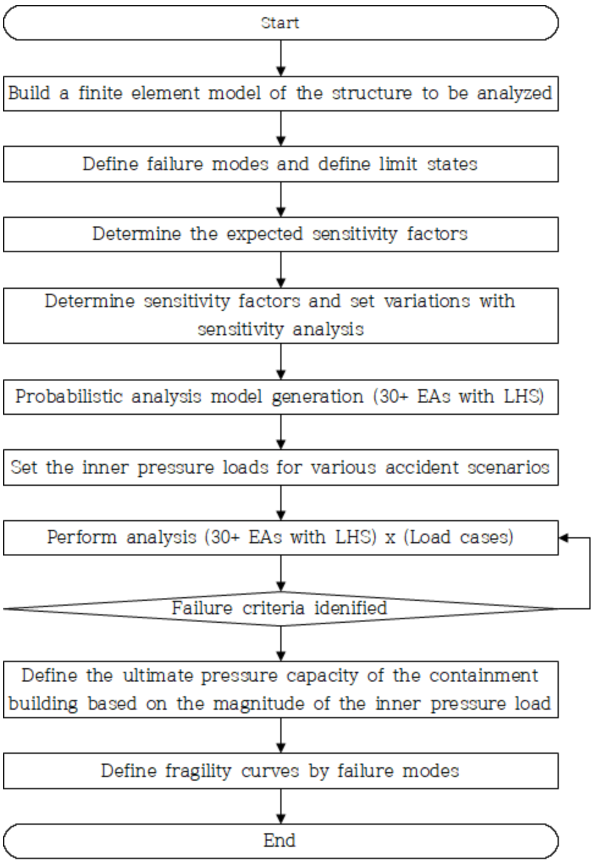

Fig. 1. A proposed method for assessing the extreme pressure performance of containment buildings.

It is important to analyze the weak areas with a preliminary analysis because the fragility curve is completely different depending on the failure mode and limit state definition. Based on the reviewed fragility areas, the main expected sensitivity factors are selected, and the uncertainty of material variables can be considered by selecting the sensitivity factors and specifying the variation range through sensitivity analysis.

ISP48 [6] defines the relationship between heat and pressure that may occur in a severe accident as follows and suggests that it should be used as an input load in the safety assessment of containment buildings.

-. Case 1: Saturated Steam Conditions,
Linearly increase pressure and temperature

-. Case 2: Station Blackout Scenario
The representative severe accident conditions, including reactor meltdowns and hydrogen explosions.

In most containment building pressure capacity evaluations, temperature and pressure are assumed to be a single load, so the loading condition is often performed as Case1. However, for Case2 loads analyzed using the MELCOR code [7], the load does not increase linearly and a very rapid increase occurs, as shown in Figure 2.

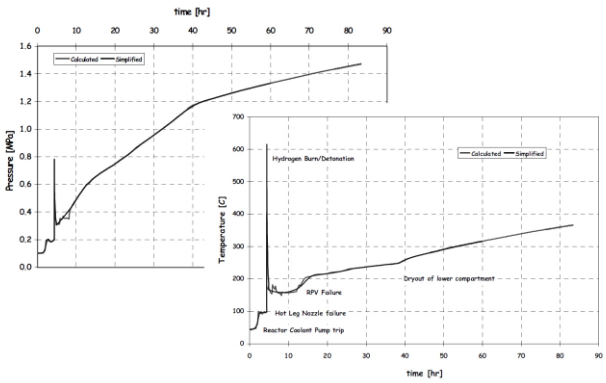

Fig. 2. Time-pressure/temperature history of station blackout scenario

The response of the structure will also be different under these loading conditions, so it is necessary to consider various load conditions.

The proposed method can be applied to generate fragility curves for each failure mode considering various loads, and HCLIF (high confidence low probability of failure) can be used to probabilistic evaluate the ultimate pressure capacity of containment buildings.

Although various loading patterns were considered, organizing the responses by loading level, the fragility curves for each mode of failure are shown in Figure 3.

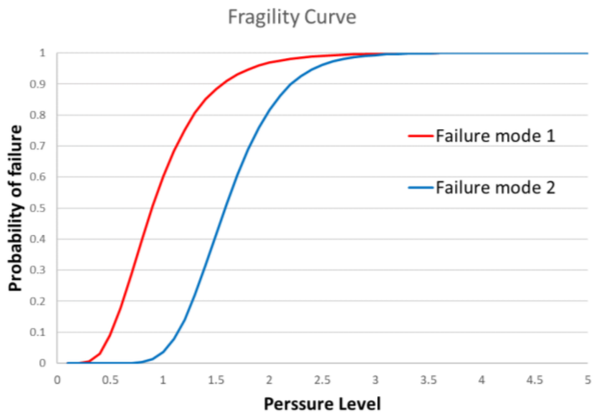

Fig. 3. Fragility curves by load level

4. Conclusions

This paper analyzes the existing studies for the evaluation of ultimate pressure capacity of containment buildings and proposes a realistic and reasonable evaluation method. Various failure modes can be considered through the three-dimensional detailed analysis model. In addition, based on the probabilistic analysis methods, uncertainties of each material variable are considered independently, and an ultimate pressure analysis method with various load combinations is proposed. By applying this analysis method, it is expected to be possible to evaluate the ultimate pressure capacity of containment buildings for various accident scenarios that have not been considered so far.

REFERENCES

[1] U.S. NRC, Containment Integrity Research at Sandia National Laboratories, NUREG-CR-6906, 2006.
[2] Moon, I.H., Noh, S.H., Lee, S.Y., Kim, K.J. Structural Behavior of PSC Reactor Containment Structure under Temperature and Pressure Loading, Journal of the Korean Society of Civil Engineers, A27(6A), pp.847-858, 2007.
[3] Kim, S.H. Three-Dimensional Structural Analysis System for Nuclear Containment Building, Journal of the Computational Structural Engineering Institute of Korea, 23(2), pp.235~243, 2010.
[4] H.T Hu, Y.H Lin, Ultimate Analysis of PWR Prestressed Concrete Containment Subjected to Internal Pressure, International Journal of Pressure Vessels and Piping, 83(3), pp.161-167, 2006.
[5] Hahm, D.G., Park, H.K., Choi, I.K., Assessment of the Internal Pressure Fragility of the PWR Containment Building Using a Nonlinear Finite Element Analysis, Journal of the Computational Structural Engineering Institute of Korea, pp.103-111, 2014.
[6] NEA, International Standard Problem NO.48 Containment Capacity, NEA/CSNI/R(2005)5, 2005.
[7] U.S. NRC, MELCOR Computer Code Manuals, NUREG/CR-6119, 2000.