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Sensitivity Analysis of Thermal Loads in the Assessment of Ultimate Pressure Capacity of Containment Building

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1. Introduction

The containment building is one of the main structures of a nuclear power plant and contains the reactor and related equipment where nuclear reactions occur. Since the containment building is the final barrier against leakage of radioactive material in the event of a severe accident, it is designed and constructed according to the relevant design regulations and is subject to safety evaluation even during operation. Nevertheless, it is necessary to evaluate the ultimate pressure capacity of containment buildings in order to respond to possible severe accidents.

Many experimental and analytical researches about ultimate pressure capacity performed around the world [1]. A significant experimental study was conducted by Sandia National Laboratories (SNL), using a one-quarter scale model of the containment building of the Ohi-3 nuclear power plant in Japan to evaluate the ultimate pressure capacity of the containment building. It is known that high thermal loads are generated simultaneously with ultimate pressure loads in the event of a severe accident such as a core melt inside the containment building, but experimental studies on this are insufficient due to practical limitations [2]. To compensate for the experimental difficulties, analytical studies have been conducted on the effect of thermal loads on the pressure resistance capacity of containment buildings, but even studies on the prediction of thermal loads generated inside containment buildings have been conducted to a limited extent.

The temperature-time histories of the containment building during the accident presented in ISP-48 Phase 3 are used as reference temperatures for design and analytical studies. Since the main material of the containment building, concrete and steel (tendons, rebar, and liner steel plates), have the characteristic of decreasing material stiffness as the thermal load increases, the ultimate pressure capacity of the containment building may be overestimated when considering only the pressure load as in the conventional evaluation method, compared to the thermal load.

Therefore, this study evaluated the ultimate pressure capacity of containment buildings subjected to ultimate pressure and thermal loads using three-dimensional finite element analysis, and analyzed the changes in ultimate pressure capacity due to the addition of thermal loads.

2. Analysis Model

2.1 PCCV 1/4 Scale Model

A finite element model was developed based on the PCCV (Prestressed Concrete Containment Vessel) 1/4 scale model experiments performed by SNL. The scale model of the containment building consists of a cylindrical wall and a hemispherical dome with a height of 16.4 meters and an outer diameter of 11.4 meters on a foundation sleeve with a thickness of 3.5 meters, as shown in Figure 1. Since the main purpose of this study is to analyze the comparative performance of ultimate pressure capacity due to the addition of thermal load, openings were excluded for the convenience of model configuration when developing the analytical model, and the rebar and tendons inside the concrete of the containment building were simulated realistically as shown in Figure 2.

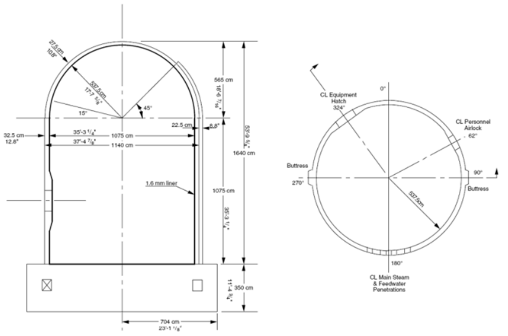

Fig. 1. 1/4 PCCV scale model section

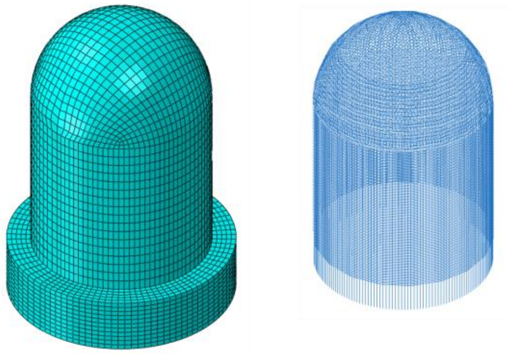

Fig. 2. Concrete walls and tendons in a scale model finite element analysis of a containment building.

2.2 Thermal Load Application

In order to evaluate the sensitivity of individual thermal loading factors, the thermal loading effect of concrete was considered in this study without considering the thermal loading effect of steel. Based on the temperature change inside the containment building in the accident scenario presented in ISP-48 as shown in Figure 3, an analysis model was developed to change the concrete material properties by applying the concrete reduction factor according to the thermal load presented in Euro-Code 2 as shown in Figure 4 [3].

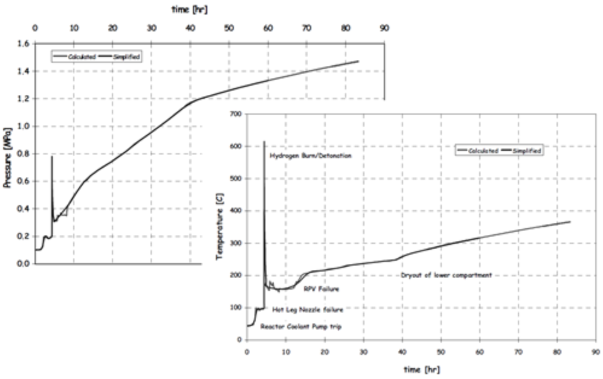

Fig. 3. Assuming time-temperature-pressure relationships in a severe accident

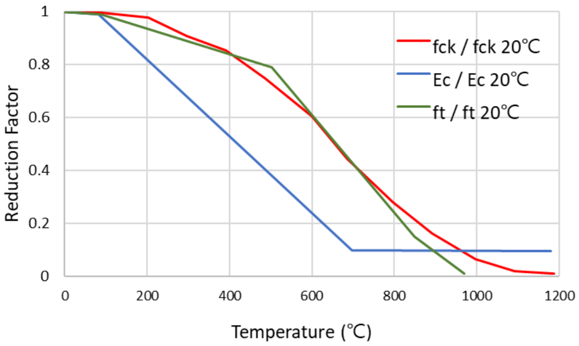

Fig. 4. Concrete reduction factor according to the thermal load

In this case, the maximum possible thermal load was applied without reflecting the increase in load over time. In addition, for the sensitivity analysis of thermal load as a probabilistic variable, the ultimate pressure capacity response to changes in thermal load was compared within a variation range of up to 20%.

3. Results of Analysis

In the ultimate pressure capacity analysis of the containment building, the failure mode was confirmed to be the failure of the center of the cylindrical wall, and no change in the failure mode was found due to the addition of thermal load. The analytical response of the containment building to additional thermal load is shown in Figure 5. Based on the displacement of 19mm in the center of the wall, the change in response value was insignificant at 100℃, and significant results occurred after 200℃. In particular, the pressure load was reduced by 3.2% at 400℃ and 7.26% at 600℃.

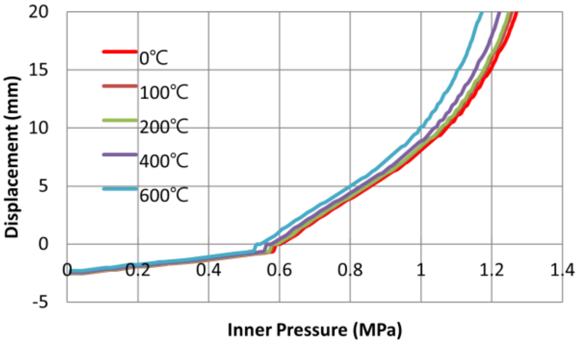

Fig. 5. Displacement response at the center of the wall in the PCCV 1/4 scale model.

4. Conclusion

In this study, the ultimate pressure capacity of the containment building was evaluated by considering the thermal load in addition to the pressure load to estimate the ultimate pressure capacity. Considering the uncertainty of the occurrence of thermal load inside the containment building, the thermal load up to 600℃ was considered, which is higher than the thermal load history presented in the references. It was found that a clear decrease in pressure capacity occurred from 200℃ and above, and at 600℃, the pressure capacity decreased up to about 7.3% based on the generated displacement. The reduction in the strength of steel under thermal loading should additionally be considered to confirm the reduction in the ultimate pressure capacity of the containment building under thermal loading. It is also necessary to more realistically evaluate the thermal loads inside the containment building in the event of a severe accident. For a more realistic analysis of the ultimate pressure capacity of containment buildings, it is recommended that thermal loads should be considered in addition to pressure loads.

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