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Sensitivity Analysis of the Ultimate Pressure Capacity of Containment Buildings to Variability in Material Properties and Thermal Loads

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1. Introduction

In this study, primarily analyzed the changes in the ultimate pressure capacity of containment buildings based on the changes in structural material properties caused by thermal loads. It is important to note that in this research did not extend to fragility assessments, but rather focused on the sensitivity analysis of the variability of structural material properties. When pressure builds up inside containment buildings, thermal loads are inevitably generated. The nature of these thermal loads varies according to severe accident scenarios. There are scenarios where the thermal load increases gradually over a long period, and others, such as hydrogen explosions, where there is a rapid increase in thermal load in a very short time. During the design of containment buildings, these thermal loads are considered to ensure pressure capacity, using somewhat deterministic methods.

Containment buildings are designed with the best technology available at the time. However, as demonstrated by the 2011 Fukushima accident, severe accidents can occur that exceed the extreme conditions considered during design. The deterioration of structural materials due to thermal loads can affect the ultimate pressure capacity of containment buildings. Therefore, it is deemed necessary to consider the changes in the properties of structural materials caused by extreme thermal loads or prolonged exposure to thermal loads.

Reviewing the literature that considers thermal loads, ACI-349-06 Appendix E primarily deals with concrete thermal expansion. Section 4.3 requires evidence that there are no impacts due to the deterioration of concrete at temperatures above 650 Fahrenheit. The internal pressure performance assessment report for US-APWR evaluates the pressure capacity under normal operation, long-term design basis accidents, and hydrogen explosions. The ultimate pressure capacity of containment buildings is evaluated differently depending on the method of applying thermal and pressure loads and the criteria for material performance degradation. There is a need to apply probabilistic methods considering various possibilities.

Therefore, this study analyzed the variability of structural material properties under various thermal load scenarios. Furthermore, by conducting a sensitivity analysis of the ultimate pressure capacity of containment buildings to the variability of structural material properties, we examined the validity of treating these properties as probabilistic variables.

2. Analysis Models and Thermal Load Application

This section describes the configuration of the analytical model, the method for applying thermal loads, and the variability of material properties.

2.1 Analysis Model

The primary objective of this study was to investigate the response changes of containment structures due to material variability, thus a relatively simple and verifiable target model was selected, like the SNL (Sandia National Laboratories) scaled model experiments[1]. The analytical model consisted of a foundation slab, cylindrical wall, hemispherical dome, tendons, rebar, and liner steel plate, with tendons and rebar assumed to be fully bonded. Material properties and tendon prestress were applied based on the literature. Figures 1 to 3 were presented to show the design drawings, analytical model, and a comparison of analytical and experimental results through graphs. Despite some discrepancies observed in the displacement-pressure load comparison at the central part of the cylindrical wall, it was concluded that an appropriate analytical model had been developed.

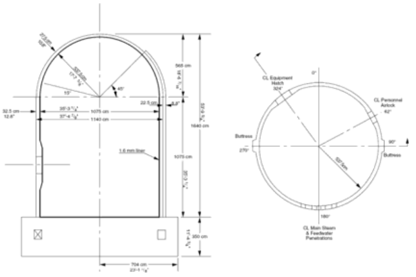


Fig. 1. 1/4 PCCV scale model section

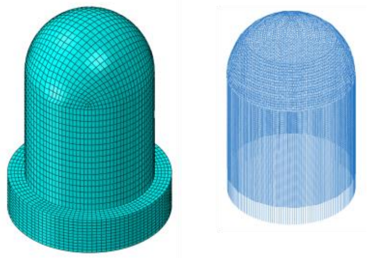


Fig. 2. Concrete walls and tendons in a scale model finite element analysis of a containment building.

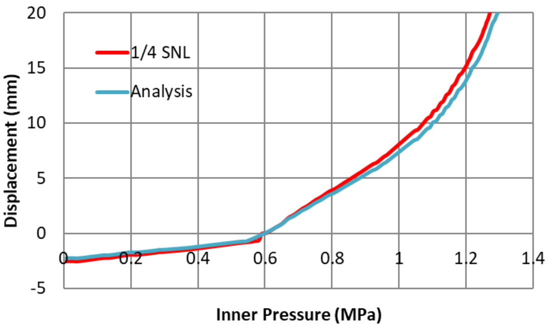


Fig. 3. Comparison of experimental and analytical results.

2.2 T Relationship Between Thermal and Pressure Loads.

In this research, four types of relationships between thermal loads and internal pressure loads were applied. As depicted in Figure 4, there is a scenario where both the internal pressure load and the thermal load increase linearly. Following that, as illustrated in Figure 5, there is a case where the thermal load remains constant at a certain level while the internal pressure load increases linearly.

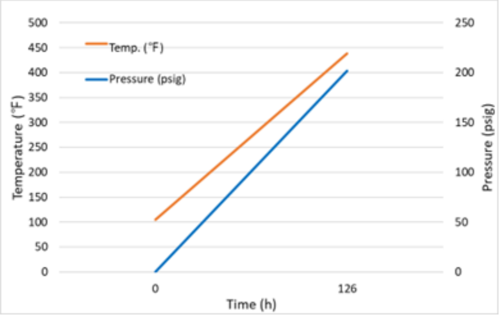


Fig. 4. Linearly increasing pressure loads and linearly increasing temperature loads.

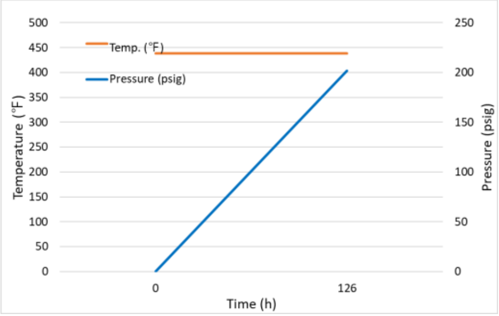


Fig. 5. Linearly increasing pressure loads and fixed thermal loads.

Based on the literature, two relationships between thermal loads and internal pressure loads were considered. Figure 6 shows the load relationship as proposed in ISP48[2], and Figure 7 displays the load relationship according to a reference document from APWR[3].

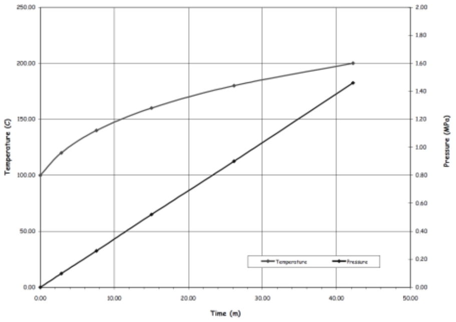


Fig. 6. The relationship between pressure and temperature loads as suggested by ISP48.

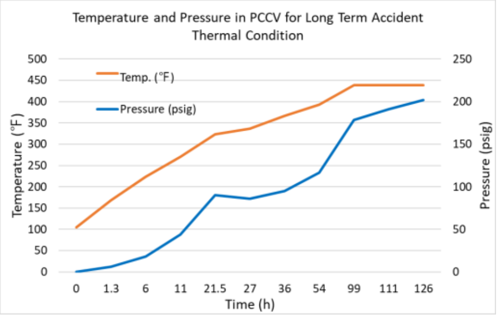


Fig. 7. The relationship between pressure and temperature loads as suggested in the US-APWR reference.

2.3 Apply Material Property Changes Due to Thermal Loads

Several methods are available for applying changes in the properties of structural materials due to thermal loads. Changes in the properties of structural materials can be applied through thermal diffusion analysis. Furthermore, changes in the properties of structural materials subjected to thermal loads, obtained through material experiments, can also be used as input data for structural analysis. In this study, input data on property changes, which allow for relatively short analysis times, were utilized to apply changes in the properties of structural materials due to thermal loads. For Euro-codes[3], as shown in Figure 8, the ratio of material property changes with increasing temperature loads is presented, while in the case of APWR reference documents, changes in material properties by temperature are provided.

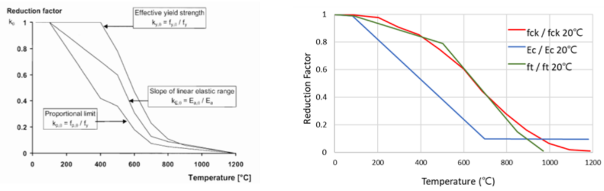


Fig. 8. Changes in material properties due to thermal loading as suggested by eurocode.

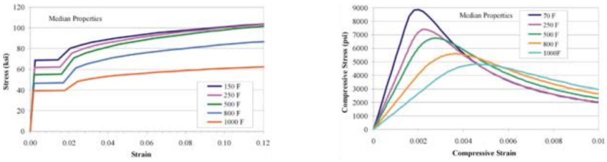
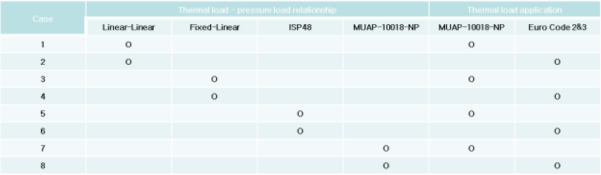


Fig. 9. Changes in material properties due to temperature loading as suggested in the APWR references.

2.4 Sensitivity Analysis Due to Material Property Changes

Based on the previously mentioned four relationships between thermal loads and internal pressure loads, as well as two types of changes in material properties, eight analysis combinations were established, as depicted in Figure 10. Custom materials were utilized to apply changes in material properties corresponding to the levels of internal pressure loads and equivalent thermal loads for each case. To analyze the response changes due to thermal loads, the maximum thermal load values were set at 500°F, 1000°F, and 1500°F, while reference materials that did not present specific thermal loads were linearly increased. A sensitivity analysis on the variability of material properties was conducted based on the displacement occurring in the central part of the cylindrical wall.



Case	Thermal load – pressure load relationship				Thermal load application	
	Linear-Linear	Fixed-Linear	ISP48	MUAP-10018-NP	MUAP-10018-NP	Euro Code 2&3
1	o				o	
2	o					o
3		o			o	
4		o				o
5			o		o	
6			o			o
7				o	o	
8				o		o

Fig. 10. Combinations of analysis.

3. Result of Analysis

Among the eight analysis cases, the one applying the internal pressure load increase pattern from the APWR reference materials did not achieve convergence in the analysis results. It is speculated that divergence occurred due to the nonlinear load increase pattern, especially when changes in material properties also had to be applied, complicating the analysis. For the sensitivity analysis on thermal loads, the analysis results for each applied temperature were summarized as shown in Figures 11 to 13. Using the analysis results at 70°F, where no thermal load was applied and hence no change in material properties occurred, as a baseline, the increase ratio of the internal pressure load when a 20mm displacement occurred in the central part of the wall is illustrated in Figure 14. Analysis case 3, which involved a fixed thermal load with a linearly increasing internal pressure load and the application of material property changes from the APWR reference materials, showed the largest increase in internal pressure load. It was observed that the response distribution varied significantly depending on the applied criteria.

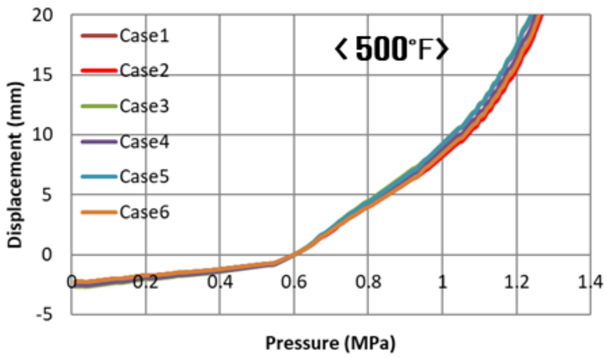


Fig. 11. Sensitivity analysis results for material property changes at 500 degrees Fahrenheit.

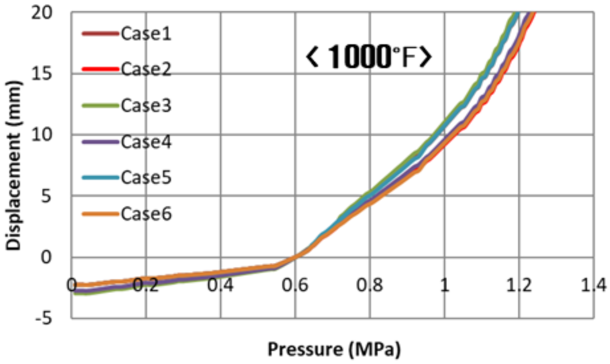


Fig. 12. Sensitivity analysis results for material property changes at 1000 degrees Fahrenheit.

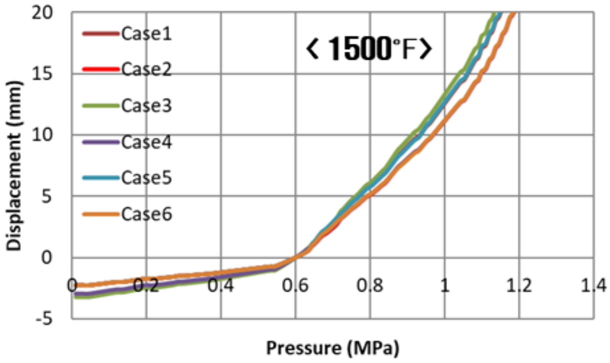


Fig. 13. Sensitivity analysis results for material property changes at 1500 degrees Fahrenheit.

Case	500°F	1000°F	1500°F
1	4.07	7.39	10.89
2	2.37	4.07	8.43
3	4.45	9.09	12.02
4	3.03	4.93	9.09
5	3.70	7.01	10.60
6	2.75	4.45	7.39

Fig. 14. 70 ˚F Based on the pressure load at 20 mm displacement of the center section of a cylindrical wall (%)

4. Conclusions

In this study, the variation in the internal pressure performance of containment buildings was analyzed through a combination of thermal load and internal pressure load relationships and thermal load application methods presented in existing literature. Analysis under six different conditions revealed a response variability range of approximately 2.4% to 12%. Based on these sensitivity analysis results, it is believed that thermal load factors should be included as probabilistic variables in deriving vulnerability curves for extreme internal pressure performance evaluations. By considering a wider variety of load application methods and changes in material properties, it is anticipated that the uncertainties associated with thermal loading can be accounted for in the evaluation of extreme internal pressure performance of containment buildings.

REFERENCES

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