Uncertainty quantification of radial displacement for Prestressed concrete containment vessel subjected to internal pressure

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1. Introduction

Nuclear containment is an essential structure in nuclear power plants, which prevents leakage of radioactive materials and protects various equipment in it to supply stably and continuously the electricity. Therefore, an accurate understanding of the structural performance of the containment is essential. One of the main factors that contaminate the performance of the containment is an increase in internal pressure due to an accident in a nuclear reactor. When the internal pressure in the containment reaches an ultimate range, containment failure occurs, and radiation materials are discharged into the atmosphere. In this study, The Finite Element(FE) model of a 1/4 scale Prestressed Concrete Containment Vessel (PCCV), on which Sandia National Lab made an experiment, is developed, and the model is validated from the experimental result. The uncertainty in the radial displacement of the liner, due to the consideration of the material's variability, is quantified through the minimum analytical results. In addition, the radial displacement of the linear is predicted through machine-learning models, and the uncertainty is re-quantified using large random datasets.

2. Finite element analysis of PCCV

2.1 Experiment and Validation of Finite Element Model

The internal pressure experiment of PCCV was conducted to evaluate the behavior and capacity of the PCCV under internal pressure at Sandia National Lab(SNL) [1]. Based on the experimental results, the different damage states in terms of internal pressure are determined, and they divide into the onset of cracking (minor damage), the onset of leakage (moderate damage), and the structural failure (major damage). The corresponding internal pressures of the PCCV are 0.78MPa, 0.98MPa, and 1.29MPa, respectively [1]. The FE model of the PCCV is developed by ABAQUS [2] software as shown in Fig 1. The PCCV model is made up of the basement, steel liner, concrete cylindrical wall, and hemispherical dome. A shell element is used for the liner, a solid element is used for the concrete structures, and a truss element is used for the rebar and tendon. Fig. 1 also compares the radial displacement results from the experiment and the FE model. It found that the FE model is well-validated against the testing data.

2.2 Finite Element Analysis for Assessing the Uncertainty in Radial Displacement

To assess the uncertainty in the radial displacement of PCCV, the material's variability, such as compressive strength and tendon force, are considered. The mean and standard deviation of the compressive strength of concrete is 48.81Mpa, and 7.76, respectively, and the normal distribution is assumed [1]. Tendon force assumes 10~50% prestressing loss with uniform distribution. 50 input datasets are randomly selected by Hypercube sampling. Also, three internal pressure values (0.78MPa, 0.98MPa, and 1.29MPa) are used as the random variable, and all input datasets are used for the FE analysis. The mean values of results at the major, moderate, and minor damage states are calculated as 23.9mm, 9.14mm, and 1.99mm, and corresponding standard deviations are 3.08, 2.03, and 1.1. However, the 50 input datasets do not represent exactly the probabilistic characteristic of the radial displacement, as shown in Fig. 2.

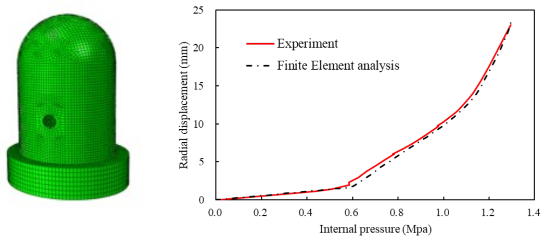

Fig. 1. Experimental and analytical responses at mid-height of the cylinder wall.

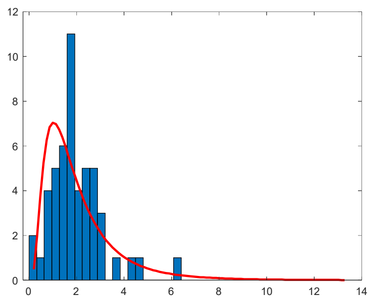

Fig. 2. Histogram and probability density function of radial displacement at minor damage state from 50 datasets

3. Prediction of radial displacement using machine-learning models

Response Surface Method (RSM) [3] and Gaussian Process Regression (GPR) [4] are used to train datasets. The datasets for training and testing the machine-learning model are obtained from the FE analysis mentioned above. Input data are the compressive strength, tendon force, and internal pressures at the defined damage states. Output data are the radial displacement; thus, a total of 50 datasets are collected, and the ratio of testing data to training data is 0.3. Fig. 4 and Table I represent the accuracy of the prediction. Both RSM and GPR models perform well, but the GPR produces the exact prediction.

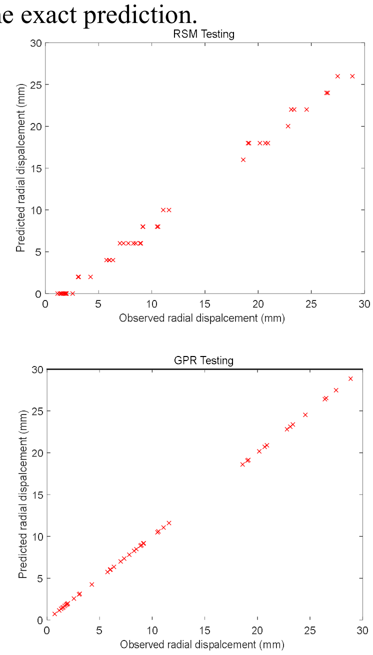

Fig. 4. Comparison of the predicted and observed radial displacement of PCCV

500 input datasets are additionally selected by Hypercube sampling, same as Section 2. The best GRR model is re-used to predict the radial displacement for the 500 input datasets. Fig. 5 and Table II represent the distribution of the radial displacement obtained from the GRP model. Also the histogram of the results obtained from the model shows a good match with the shape of the expected distribution as shown in Fig 6. Thus, the machine-learning model could accurately estimate the uncertainty using more datasets without additional FE analysis.

4. Conclusions

In this study, the uncertainty in the radial displacement of the PCCV is quantified. For this purpose, the FE model of PCCV is developed and validated against the experimental data. The FE analysis is conducted with 50 random input datasets, and the uncertainty in the radial displacement is quantified. However, the 50 input datasets are not sufficient to estimate the probabilistic characteristic of the uncertainty in the radial displacement. Thus, the machine-learning model is developed using the obtained analytical data and can predict large amounts of radial displacements from unknown input variables. As a result, the uncertainty in the radial displacement with 500 random input datasets is more efficiently and reasonably quantified by the best machine learning model trained using the small number of FE results.

Table I: Performance of machine-learning models

		R^2	Root mean square error
RSM	Training	0.956	2.024
	Testing	0.946	2.037
GPR	Training	1.0	0.0046
	Testing	1.0	0.0038

Table II: Probabilistic response of radial displacement of PCCV using GPR for 500 random datasets

Limit state	Major	Moderate	Minor
Mean (mm)	23.9	9.19	2.15
Standard deviation	3.35	2.15	0.98

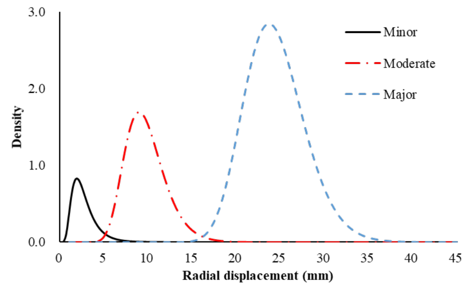

Fig. 5. Probabilistic response of radial displacement of PCCV using GPR

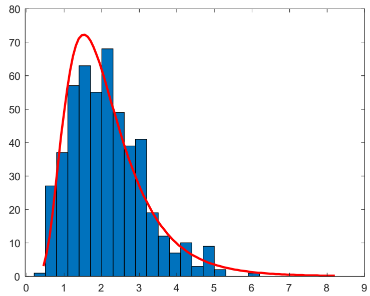

Fig. 6. Histogram and probability density function of radial displacement at minor damage state obtained from 500 datasets

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