A Comparative Study on Ultimate Pressure Capacity Evaluation Parameters of Small Modular Reactor Steel Containment Vessel

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Keywords : failure criteria, finite element method, small modular reactor, steel containment vessel, ultimate pressure capacity

1. Introduction

Nuclear power plant (NPP) containment structure plays a role of barrier that preventing the release of hazardous radioactive materials and the integrity should be maintained during accident conditions. Accordingly, numerous studies have been performed to evaluate the ultimate pressure capacity (UPC) of concrete containment building in large-scale NPPs [1].

With the global development of small modular reactors (SMRs), new types of steel containment vessel (CV) were adopted. Due to the differences in design parameters such as material and geometry, the establishment of a new evaluation method is required.

In this study, UPC evaluations were conducted for innovative SMR (i-SMR) steel CV. The structural behavior under internal pressure condition was assessed by using finite element (FE) analysis. Additionally, appropriate evaluation parameters were proposed by incorporating strain- and stress- based failure criteria.

2. Evaluation Model and Conditions

2.1 Failure criteria

The regulatory guides in the United States [2] and the Republic of Korea [3] define 1.5% membrane strain-based failure criterion for steel CV. However, this criterion was developed for large-scale NPPs and further discussion is needed to determine whether the membrane criterion can be applied. Therefore, equivalent and maximum principal strain were selected along with membrane strain as evaluation parameters and the results were compared.

In addition, analyses considering stress were carried out. Accordingly, the design limit value was selected as the stress-based failure criterion which is specified in the Level C service conditions of the American Society of Mechanical Engineers (ASME) Code Sec. III Div. 1 Subsection NB [4]. Depending on the requirements, 483 MPa was used as the criterion. von-Mises stress, maximum principal stress and membrane stress intensity were selected as evaluation parameters.

2.2 Evaluation model

The evaluation model was constructed by using FE analysis program ABAQUS [5] as shown in Fig. 1. As a major penetration, only the steam generator (SG) inspection flange was taken into account. Additionally, the CV ledge was considered for gravity effects of internal structures.

The continuum, 3D, 8-node with reduced integration and 8-node linear heat transfer brick elements were used for structural and thermal analysis, respectively. A total of 89,370 nodes and 61,896 elements were used in the model.

The materials were selected as SA-533 Type B, Class 2 for the upper section and SA-965 Type FXM-19 for the lower section. Since elasto-plastic properties are required for UPC calculation, true stress-strain curve was constructed by using the equations provided in ASME Code Sec. VIII [6].

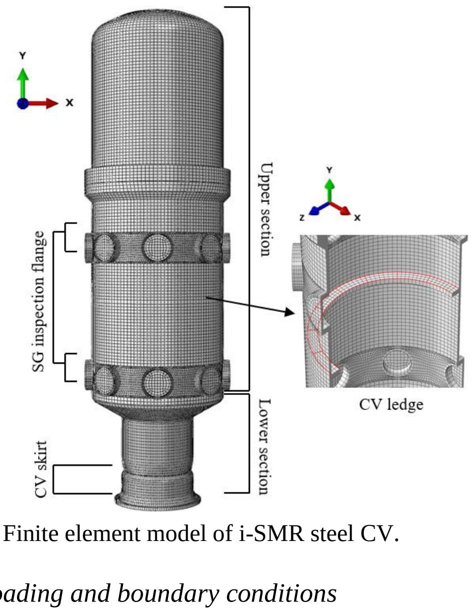

Fig. 1. Finite element model of i-SMR steel CV.

2.3 Loading and boundary conditions

The analysis was conducted in two steps following the regulatory guide. In step 1, gravity was applied to the entire model, while the design pressure (5 MPa) and design temperature (350°C) were applied to the inner wall of the CV. In addition, the weight of internal structures was applied to the upper surface of the CV ledge. In Step 2, an incrementally increased internal pressure was defined as a loading condition until the analysis is terminated. The bottom surface of the CV skirt was fully fixed throughout all steps. These conditions are presented in Fig. 2.

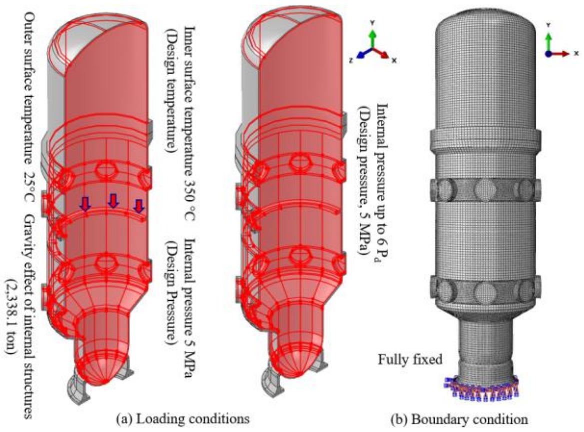

Fig. 2. Schematics of loading and boundary conditions.

3. Evaluation Results

Fig. 3 shows the contour of von-Mises stress, maximum principal stress and maximum principal strain. The analysis was terminated at 20.5 MPa and the maximum values were observed near the SG inspection flange, followed by the transition region.

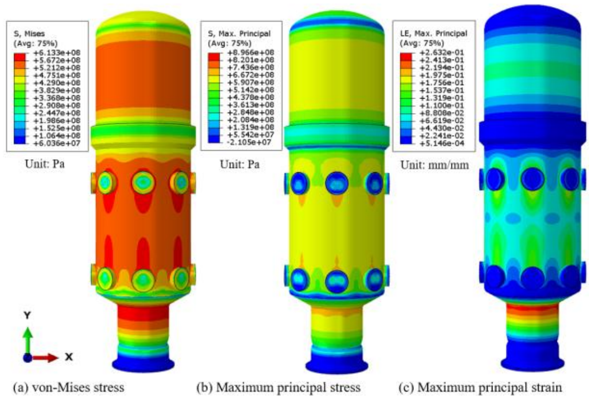

Fig. 3. FE analysis results at 20.5 MPa.

According to the regulatory guide, UPC should be evaluated in the area that is away from the discontinuities. The areas for each parameter were determined by comparing the UPC values along the height and circumferential directions. In Fig. 4, the results were compared for each parameter at the point where the lowest value was observed within the free-field. It was confirmed that maximum principal stress is the most conservative parameter for stress-based evaluation, while membrane strain is for strain-based evaluation. In addition, the membrane strain-based UPC provided the most conservative value among all the parameters.

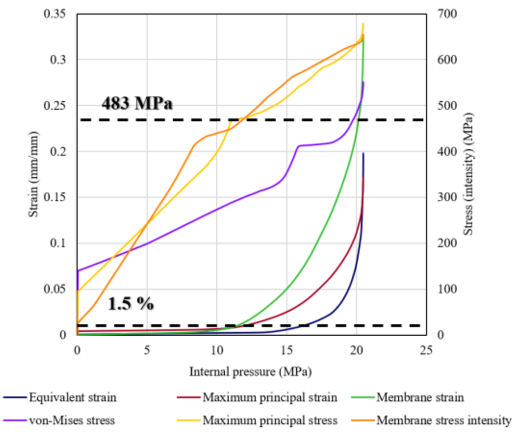

Fig. 4. Comparison of evaluation results.

4. Conclusions

In this study, UPC evaluations were conducted for i-SMR steel CV. The results were compared and analyzed using various stress and strain parameters.

(1) Under internal pressure load, the maximum stress and strain were observed at the penetration when the pressure reached 20.5 MPa.
(2) Membrane strain was found to be the most conservative in strain-based evaluation, which remained valid when considering both stress and strain parameters.
(3) The variation in the results is primarily due to the different physical meanings of the parameters. For a conservative evaluation, an assessment based on membrane strain appears to be necessary.

ACKNOWLEDGMENTS

This work was supported by the Innovative Small Modular Reactor Development Agency grant funded by the Korea Government (MOTIE) (No. RS-2024-00405419).

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