

Influence of Impact Direction on the Local Structural Response of an i-SMR Steel Containment Vessel

Kyeong Seo Lee^a, Min Jeong Park^b, Yoon-Suk Chang^{a*}

^aDepartment of Nuclear Engineering, Kyung Hee University

1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do 17104, Republic of Korea

^b Graduate School, Department of Nuclear Engineering, Kyung Hee University

1732 Deogyeong-daero, Giheung-gu, Yongin-si, Gyeonggi-do 17104, Republic of Korea

*Corresponding author: yschang@khu.ac.kr

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1. Introduction

A containment vessel (CV) serves as the final physical barrier of a nuclear power plant and is required to maintain its structural integrity under various loading conditions. Impact events can produce highly localized stress and permanent plastic deformation, and the resulting response may vary depending on the impact direction relative to the local structural geometry. With the development of small modular reactors (SMRs), steel CVs have been increasingly adopted, highlighting the need to evaluate how impact direction affects their structural response.

In this study, finite element (FE) analyses were performed to investigate the effect of impact direction on the local response of an i-SMR steel CV. Three impact directions, corresponding to vertical, intermediate, and local wall-normal orientations, were considered. The structural responses were compared using equivalent plastic strain and von-Mises stress.

2. FE Analyses

2.1 Analysis Model

Explicit dynamic analyses were performed using ANSYS Mechanical LS-DYNA [1]. As shown in Fig. 1, the FE model included the transition region and portions of the upper and lower sections. A hypothetical stud-nut assembly was represented as the impactor and modeled as a rigid body. The steel CV was discretized using 28,727 eight-node hexahedral solid elements with reduced integration.

2.2 Material properties

For the upper section, SA-533 Type B Class 2 low-alloy steel was considered, whereas SA-965 Type FXM-19 austenitic steel was adopted for the lower section because of its resistance to irradiation-induced embrittlement. The elastic-plastic behavior of both materials was represented using a piecewise linear plasticity model. The yield strength, Young's modulus, and Poisson's ratio were obtained from ASME BPVC Section II, Part D [2], using the values at room

temperature. The true stress-strain curves at the same temperature were defined based on the nonlinear stress-strain formulation in ASME BPVC Section VIII, Division 2, Annex 3-D [3].

2.3 Analysis conditions

Three impact cases were considered to examine the effect of impact orientation, as shown in Fig. 2. With respect to the X-Z plane, vertical (90°), intermediate (75°), and local wall-normal (60°) impact directions were defined. An initial velocity of 16.8 m/s was applied based on the free-fall condition. The bottom surface of the steel CV was constrained, and surface-to-surface contact was defined between the steel CV and the impactor.

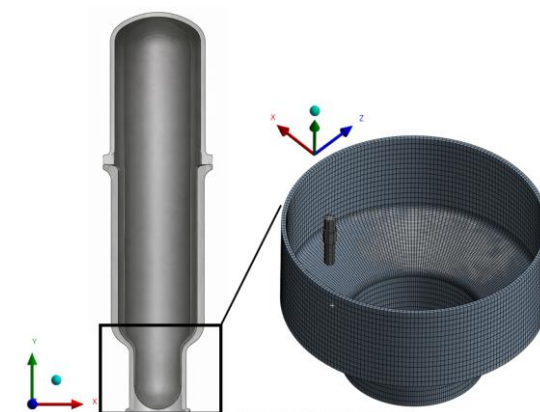


Fig. 1. Steel CV configuration and FE model

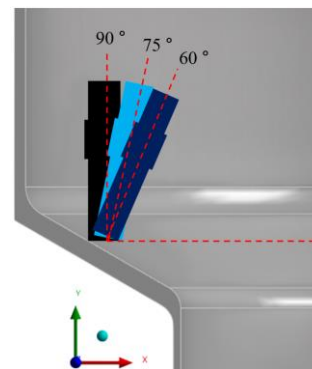


Fig. 2. Impact directions considered in the analyses

3. Analysis Results

The analysis results are shown in Fig. 3. The equivalent plastic strain ranged from approximately 0.7% to 7.1%, while the von-Mises stress ranged from 358 to 421.5 MPa. The key results are summarized in Table I.

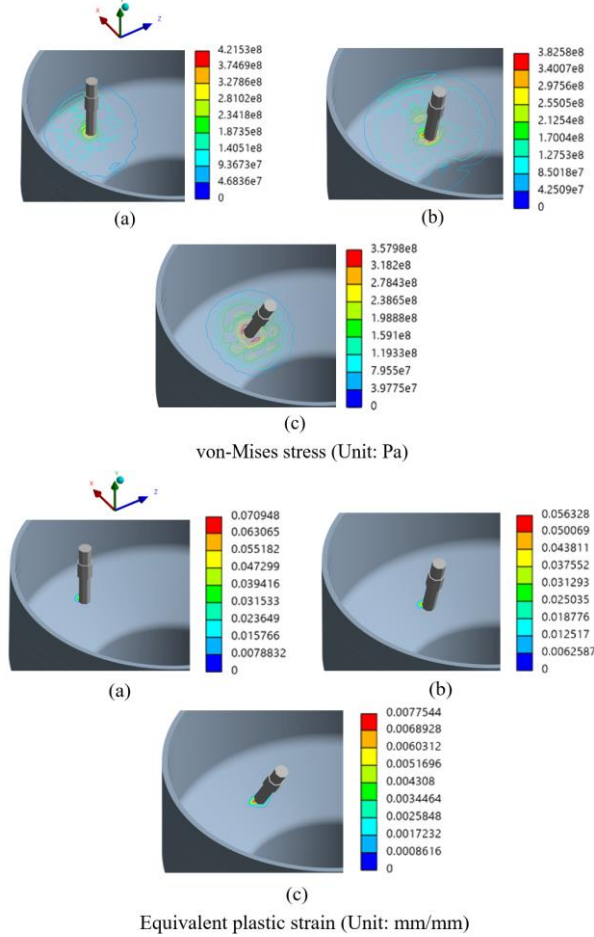


Fig. 3. von-Mises stress and equivalent plastic strain distributions for different impact directions: (a) 90°, (b) 75°, and (c) 60°.

Table I: Summary of impact analysis results

Impact direction	Max. equivalent plastic strain (%)	Max. von-Mises stress (MPa)
90 °	7.09	421.5
75 °	5.63	382.6
60 °	0.78	358.0

Both parameters reached their maximum values in the 90° case and became smaller toward the local wall-normal orientation. Compared with the 90° case, the 60° case showed approximately 89% and 15% lower maximum equivalent plastic strain and von-Mises stress, respectively.

In all three cases, the equivalent plastic strain was

highly localized near the contact region. These results indicate that the impact direction relative to the local wall geometry has a significant influence on the local structural response of the steel CV.

Structural integrity was further evaluated based on the calculated strain response. Referring to Refs. [4] and [5], the minimum reduction in area specified in the ASME Code was converted to the true strain and adopted as a strain-based failure criterion. The resulting value of 69.3% was used for comparison with the equivalent plastic strain. Since the maximum equivalent plastic strain obtained in all impact cases remained below this limit, the strain-based failure criterion was not reached under the assumed impact conditions.

4. Conclusions

In this study, explicit dynamic FE analyses were conducted to investigate the effect of impact direction on the local structural response of an i-SMR steel CV. The main conclusions are summarized as follows:

- (1) The maximum von-Mises stress and equivalent plastic strain were approximately 421.5 MPa and 7.1%, respectively.
- (2) Both parameters reached their maximum values under the 90° impact condition and decreased toward the local wall-normal direction, indicating that impact direction significantly affects the structural response of the steel CV.
- (3) The maximum equivalent plastic strain remained below the 69.3% strain-based failure criterion for all impact directions considered, indicating that the criterion was not reached even under the most severe analyzed condition.

ACKNOWLEDGMENTS

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