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Structural Response and Damage Evaluation of Major Primary- and Secondary-System Components under Steam Explosion Loads during ERVC Conditions

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1. Introduction

During severe accidents, molten corium may interact with cooling water in the reactor cavity, potentially leading to a steam explosion [1,2]. In particular, when the external reactor vessel cooling (ERVC) strategy is applied, the presence of cooling water significantly alters pressure wave propagation, reflection, and attenuation characteristics. The resulting impulsive loads may impact the structural integrity of major primary- and secondary-side plant components. The reactor coolant system (RCS) includes the reactor pressure vessel (RPV), hot leg piping, and the primary side of the steam generator (SG), while the secondary system includes the main steam line (MSL).

Previous studies on steam explosion phenomena have primarily focused on pressure wave propagation or structural integrity of the reactor cavity [3,4,5]. In contrast, the present study extends the scope of structural evaluation to major primary- and secondary-side components, including RCS components (the hot leg piping and the primary side of the steam generator) and the main steam line, under ERVC conditions.

In this study, we numerically evaluate the structural responses of the RPV, its support system, hot leg piping, the primary side of the steam generator, and the main steam line when subjected to steam explosion loads under ERVC conditions. This assessment is conducted from a deterministic structural integrity perspective to confirm conservative structural safety margins for the major primary and secondary systems under ERVC conditions and to provide reference data for regulatory-oriented structural evaluations..

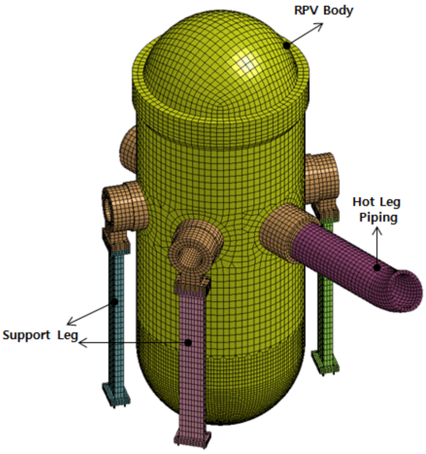
2. Finite Element Modeling and Analysis Methodology

2.1 FE Modeling of Major Primary- and Secondary-Side Components

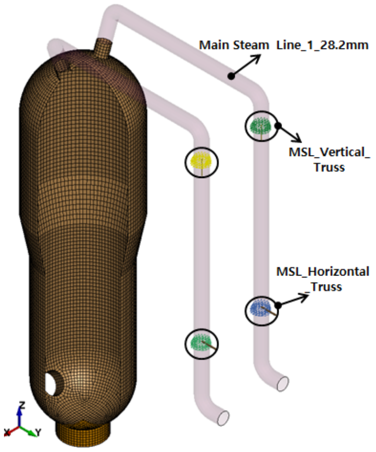
A three-dimensional finite element (FE) model was developed to evaluate the structural responses of major primary- and secondary-side components under ERVC conditions. The model includes the reactor cavity, RPV, reactor coolant system (RCS) piping, the primary side of the steam generator, hot leg piping, and the main steam line (MSL). The RPV, RCS piping, and RPV support system were modeled using three-dimensional solid elements to accurately represent global structural behavior, as shown in Fig. 1(a) [6]. The connections between the RPV supports and the reactor cavity were represented by one-dimensional beam elements with equivalent cross-sectional areas to simulate anchor bolts [6].

The steam generator (primary side) and main steam line were modeled using shell elements, as shown in Fig. 1(b) [6]. In particular, the main steam line supports were represented by one-dimensional truss elements with equivalent stiffness derived from linear spring coefficients for horizontal and vertical support conditions. The steam generator supports were conservatively modeled as rigid, fully constraining all degrees of freedom. All steel components were modeled using the *MAT_PLASTIC_KINEMATIC material model in LS-DYNA to account for strain-rate effects [6].

Details of the material models for concrete, steel, and the liner plate, as well as the finite element modeling of the reactor cavity details (e.g., element types and boundary conditions) have been described in previous studies [7,8].



(a) Reactor pressure vessel and its support system, hot leg pipe



(b) Steam generator and main steam line

Fig. 1. Finite element model of major primary- and secondary-side components [6]

2.2 Steam Explosion Load Modeling

Steam explosion loads were simulated by converting the thermal energy of molten corium into an equivalent TNT explosion. Under ERVC conditions, the cooling water level in the reactor cavity was assumed to be 7.0 m. Based on the molten corium jet mass and thermal energy, the maximum energy conversion ratio provided by the TEXAS-V code was conservatively adopted to establish an upper-bound loading condition, rather than to represent a realistic steam explosion scenario. This resulted in an equivalent TNT mass of 5.3 kg, corresponding to the upper-bound steam explosion loading condition, which intentionally exceeds expected realistic energy conversion levels to ensure sufficient structural safety margins from a regulatory perspective [6].

Under the ERVC strategy, steam explosion loads acting on the RPV were applied as input for the structural analysis. Shock waves generated by the steam explosion propagate through the cooling water and induce reflected pressure loads on the RPV. As shown in Fig. 2, the reflected pressure loads acting on the RPV and reactor cavity were simulated using coupled Arbitrary Lagrangian-Eulerian (ALE) and fluid–structure interaction (FSI) methods [6]. Under ERVC conditions, the steam explosion produced highly conservative reflected pressure and impulse levels at the reactor cavity bottom slab, reaching 2010 MPa and 126 MPa·ms within 5.0 ms, respectively. These localized extreme values are characteristic of near-field impulsive loading in equivalent TNT-based analyses and were stably captured through the coupled ALE–FSI framework without inducing numerical instability [6].

Pressure sensors (tracers) were embedded at four locations (B1–B4) beneath the RPV model to capture spatial variations in reflected pressure and impulse, as shown in Fig. 3 [6]. The predicted reflected pressure histories were directly applied as time-dependent loads in the FE structural analysis. As summarized in Table 1, the maximum reflected pressure was 16.6 MPa at location B1, while locations B2–B4 exhibited peak pressures of approximately 9.3–9.4 MPa [6]. The corresponding reflected impulses were relatively uniform, ranging from 18.0 to 19.3 MPa·ms. These results indicate that although extremely high reflected pressure and impulse were generated locally at the reactor cavity bottom slab under ERVC conditions, the impulsive loads were significantly attenuated as they propagated upward through the cooling water. Consequently, this resulted in substantially reduced pressure and impulse levels acting on the RPV [6].

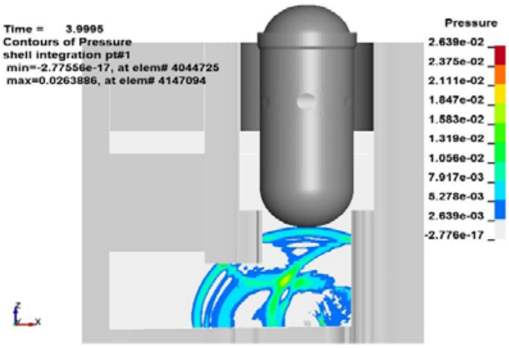


Fig. 2. Simulation of reflected pressure loads using coupled ALE and FSI methods [6].

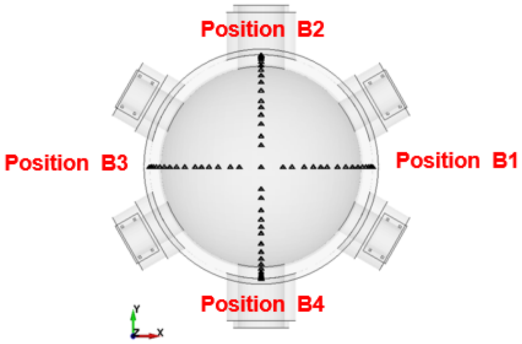


Fig. 3. Schematic of pressure sensor locations at positions B1 to B4 [6]

Table. 1. The maximum reflected pressure and impulse at each location [6]

Position	Max. pressure (MPa)	Max. impulse (MPa·ms)
B1	16.6	18.0
B2	9.4	18.8
B3	9.3	19.3
B4	9.4	18.7

3. Numerical results

3.1. Structural Response and Damage Evaluation of the RPV and Support System

The structural responses of the RPV were evaluated by examining displacements and stress responses at the upper and lower surfaces along the vessel centerline. The maximum displacements at the upper surface were 1.50 mm, 1.42 mm, and 2.60 mm in the x-, y-, and z-directions, respectively. At the lower surface, the maximum displacements were -1.11 mm, -2.14 mm, and 2.99 mm in the corresponding directions. All displacement responses remained within a few millimeters, indicating negligible global deformation. The maximum von-Mises stress in the RPV was predicted to be 53.80 MPa at 5.99 ms after the steam explosion, as seen in Fig. 4. This value is significantly lower than the yield strength of the RPV material (429 MPa), indicating elastic behavior throughout the analysis duration [6].

The analysis showed that the maximum von-Mises stresses in the RPV support system (56.67 MPa) and anchor bolts (310.76 MPa) did not exceed their respective yield strengths of 273 MPa and 1,062 MPa, thereby ensuring structural integrity within the elastic range, as shown in Fig. 5 [6]. In particular, the maximum tensile strain in the anchor bolts was 0.16%, which is well below the ductile failure criterion of 5.0% [9], as shown in Fig. 6 [6]. These responses were obtained under conservative steam explosion loading conditions, and no damage compromising the overall structural integrity of the RPV or its support system was predicted. This comparison demonstrates that the severe local loading conditions generated at the reactor cavity bottom slab are effectively mitigated by wave attenuation in the cooling water, such that the reflected pressure and impulse loads applied to the RPV remain at conservative yet structurally manageable levels. As a result, the RPV and its support system exhibit limited displacement and stress responses despite the highly conservative steam explosion loading assumptions [6].

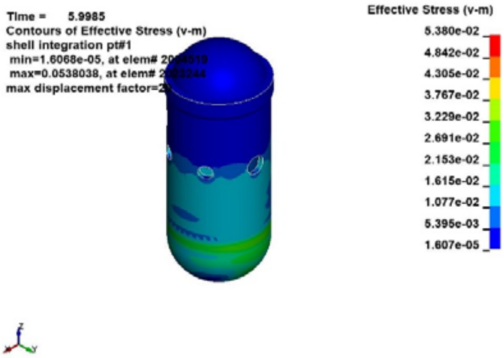
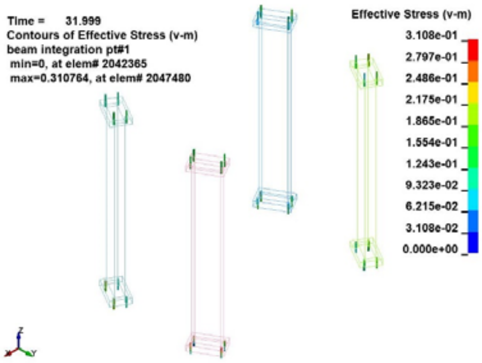


Fig. 4. The von-Mises stress contour of the RPV [6]

(a)



(b)

Fig. 5. The von-Mises stress contours of RPV support system (a) and anchor system (b) [6]

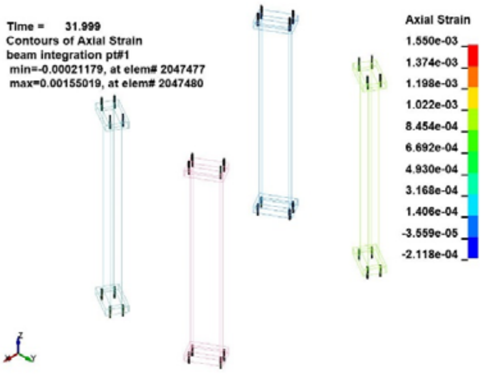


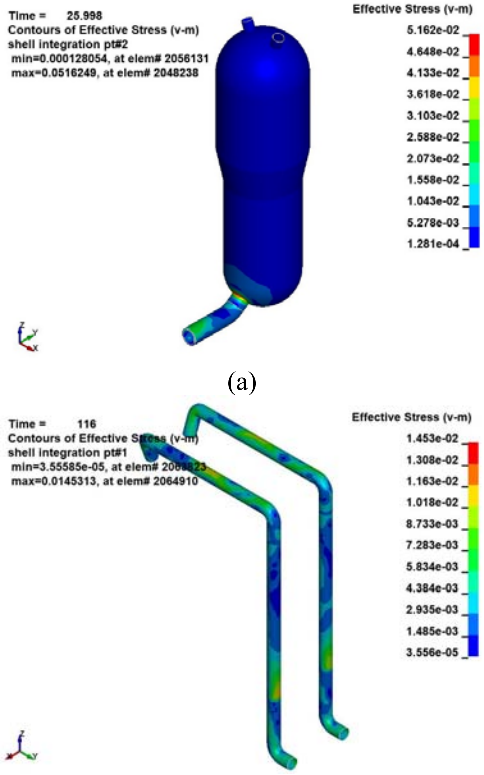
Fig. 6. The axial strain contour of RPV support system [6]

3.2. Structural Response and Damage Evaluation of the Hot Leg, Primary Side of the Steam Generator, and Main Steam Line

The displacement responses of the primary side of the steam generator were evaluated at the upper and lower surfaces as well as at the hot leg connection. The maximum displacements at the upper surface were 0.54 mm, 1.24 mm, and 0.00 mm in the x-, y-, and z-directions, respectively. For the hot leg piping, the maximum displacement in the z-direction at the RPV connection was 2.07 mm, which is insufficient to induce structural damage. In the case of the main steam line (secondary side), the maximum displacement in the y-direction at the support locations ranged from 1.51 mm to 1.64 mm, while displacements at the head fitting connection were less than 0.02 mm, indicating near-rigid behavior at the penetration region [6].

The maximum von-Mises stresses were 28.30 MPa for the hot leg piping and 51.63 MPa for the primary side of the steam generator, as shown in Fig. 7(a), which are significantly lower than their corresponding yield strengths of 273 MPa and 429 MPa, respectively [6]. The maximum von-Mises stress for the main steam line was 14.53 MPa, as shown in Fig. 7(b), which is also well below its yield strength of 276 MPa [6].

In particular, the maximum principal strain in the main steam line was predicted to be 0.008%, indicating negligible deformation even under conservative loading conditions. The attenuation of impulsive loads during upward propagation significantly limits their transmission to the connected piping systems, resulting in minimal structural responses in the hot leg piping, steam generator, and main steam line, as evidenced by the low stress levels relative to their yield strengths and the negligible principal strain observed in the main steam line [6].



(a)

(b)

Fig. 7. The von-Mises stress contours of the hot leg piping and steam generator (a), and main steam line (b) [6]

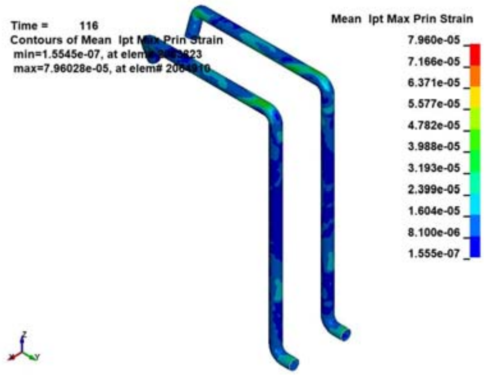


Fig. 8. The maximum principal strain contour of the main steam line [6]

4. Conclusions

A numerical assessment of structural responses to steam explosion loads under ERVC conditions was performed for the RPV, its support system, hot leg piping, the primary side of the steam generator, and the main steam line (secondary system). The analysis results demonstrate that the displacements, stresses, and strains in all evaluated components remain well below the corresponding yield and failure criteria. The structural integrity of the primary system and secondary system is maintained.

The results of this study demonstrate that, although steam explosion events under ERVC conditions can generate severe local loading at the reactor cavity bottom slab, these impulsive loads are effectively mitigated by wave attenuation in the cooling water. Consequently, the reflected pressure and impulse loads applied to the RPV and connected primary- and secondary-side components remain at conservative yet structurally manageable levels.

Acknowledgements

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