Numerical Analysis of Structural Integrity Assessment of the Reactor Cavity During a Steam Explosion Using Load-Mapping Technique

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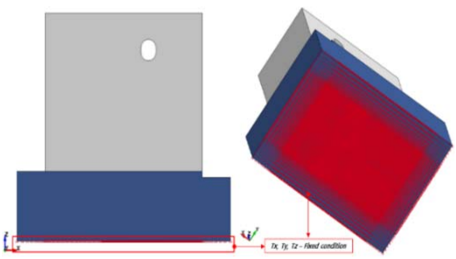
1. Introduction

From a deterministic structural integrity perspective, the primary considerations in evaluating reactor cavities subjected to steam explosion loads involve potential damage to reactor cavity walls and floors. Such damage may result in the release of radioactive substances. Limited research has been conducted specifically to examine the effects of explosion loads on reactor containment structures and their components [1–5]. Prior studies primarily utilized computational fluid dynamics (CFD) or hydrodynamic codes to model pressure profiles generated by steam explosions [1–4]. These profiles were subsequently integrated into finite element analyses to quantitatively assess the dynamic response and structural integrity of reactor cavity components or structures [1–4]. This study employs a computational approach to preliminarily evaluate the structural integrity of the reactor cavity under steam explosion loads using a load-mapping technique.

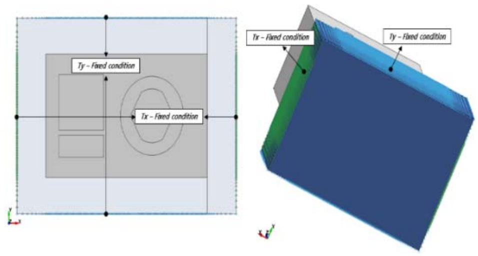
2. Finite Element Modeling

2.1 FE Modeling

The finite element structural model of the reactor cavity employed in this study was developed based on geometric data from a PWR-type reactor. The finite element model of the reactor cavity and basemat, subjected to steam explosion loads, utilized a mesh size of 150 mm [5]. Regions distant from the explosion site were modeled using a coarser mesh size of 250 mm [5]. The concrete of reactor cavity and basemat was represented using 3D solid elements, while the liner plate was modeled using 2D shell elements [5]. Reinforcements were simulated using one-dimensional beam elements [5]. All nodes of the basemat concrete that were in contact with the exterior liner plate bonded to the reactor cavity were constrained (Fig. 1(a)), with symmetry boundary conditions applied to simulate structural continuity (Fig. 1(b)) [5,7].



(a)



(b)

Fig. 1. Boundary and symmetric conditions [5,7]

2.2 Material Models

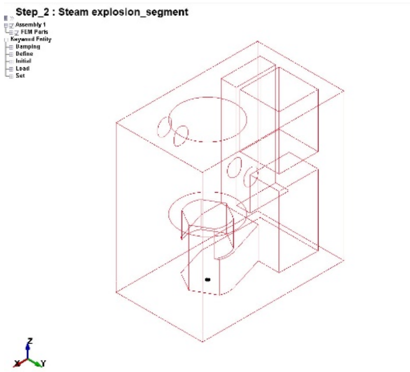
Concrete of the reactor cavity and basemat was modeled using the KCC concrete model in LS-DYNA, which automatically generates nonlinear concrete parameters based on defined density, Poisson's ratio, and compressive strength [6]. To simulate strain rate effects on concrete, dynamic increase factors were applied [6].

Reinforcements and liner plate were modeled using the plastic kinematic hardening model in LS-DYNA, which accounts for strain-rate effects, isotropic hardening, and the Bauschinger effect [6].

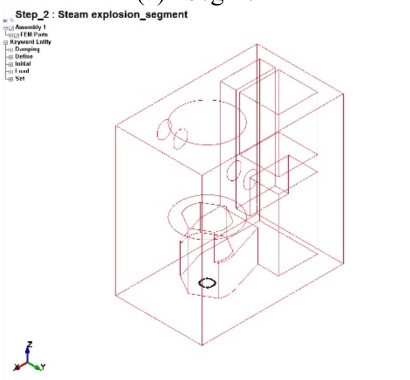
2.3 Load-Mapping Technique

The steam explosion loads were applied at the junction of the reactor pressure vessel centerline and the bottom slab of the reactor cavity. The load-mapping technique was employed to simulate steam explosion loads within the reactor cavity. To apply loading conditions, pressure-time curves were mapped onto segmented surface areas using the *Set_Segment option in LS-DYNA [7]. As illustrated in Fig. 2, the reactor cavity surface was divided into 18 segments to accurately simulate spherical wave propagation [7].

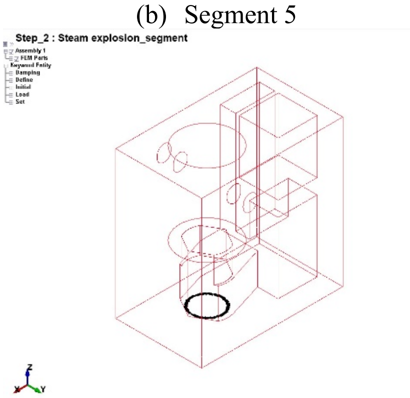
In this study, the incident pressure waves generated by the TEXAS-V code were conservatively amplified by a factor of approximately two to account for reflected pressure waves [7]. Pressure-time curves for each segment were determined based on attenuation ratios and wave propagation velocity (1500 m/sec), as depicted in Fig. 3 [7]. In particular, the attenuation of reflected pressure waves with increasing distance from the explosion source was modeled using Cole's correlation [7].



(a) Segment 1



(b) Segment 5



(c) Segment 10

Fig. 2. Example of the segments for load-mapping [7]

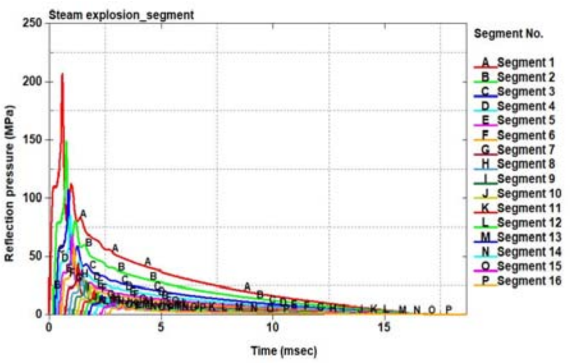
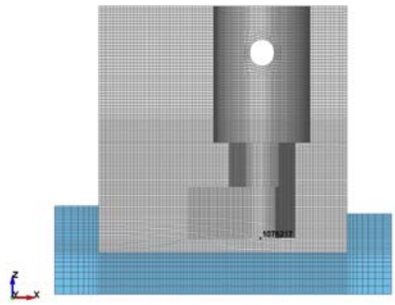


Fig. 3. Pressure-time histories of the reflected shock waves for each segment [7]

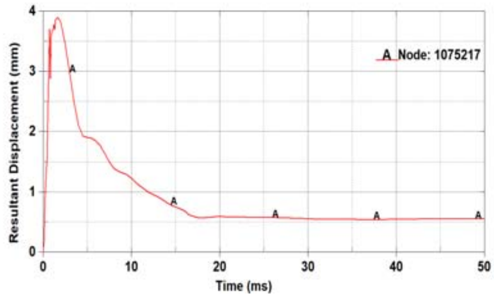
3. Structural Integrity Evaluation

3.1. Resultant Displacement

Figures 4(a) and 4(b) illustrate the target point at the bottom slab and the resultant displacement-time history at this point during the steam explosion, respectively. The maximum resultant displacement at the target point was 3.89 mm at 1.60 ms. The residual displacement at the target point after 50 ms was 0.55 mm.



(a)



(b)

Fig. 4. Scheme of the target point at the bottom slab (a) and the resultant displacement-time history at this point (b) [7]

3.2. Concrete Damage

Concrete damage was evaluated using a shear strain threshold of 0.5%, in accordance with guidelines specified in NEI 07-13 [8]. As shown in Fig. 5, the maximum shear strain reached 0.38% at 2.5 ms near a corner region [7]. This result indicated that no localized concrete damage occurred due to the steam explosion loads [7].

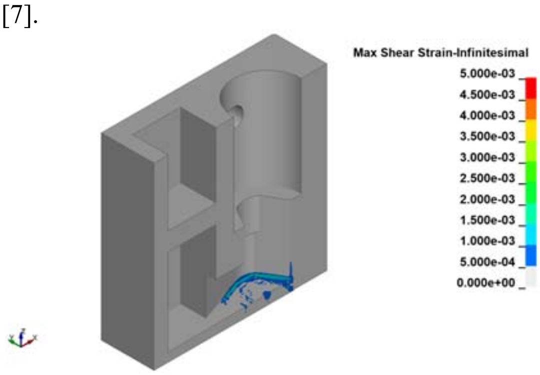


Fig. 5. The maximum shear strain contour of the concrete in the reactor cavity [7]

3.3. Reinforcements Damage

As depicted in Fig. 6, the maximum axial strain in the reinforcements was predicted to be 0.17% at 2.5 ms [7]. The axial strain did not exceed the failure criterion of 5.0% specified in NEI 07-13 [8]. Thus, no damage to reinforcements was expected under the steam explosion loads [7].

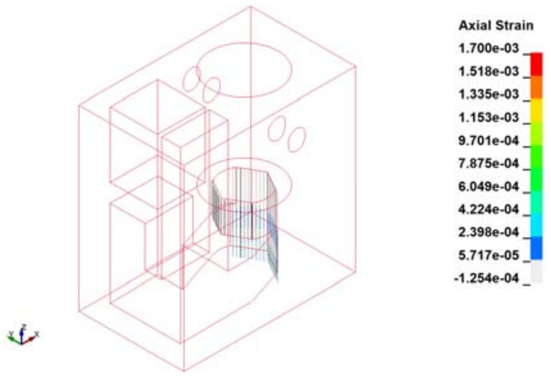


Fig. 6. The axial strain contour of the reinforcements [7]

3.4. Liner Plate Damage

As illustrated in Fig. 7, the maximum principal strain in the exterior liner plate was approximately 0.037% at 1.0 ms [7], which is well below the ductile failure threshold of 5.0% recommended by NEI 07-13 [8]. Consequently, no damage to the exterior liner plate was predicted subjected to the steam explosion loads [7].

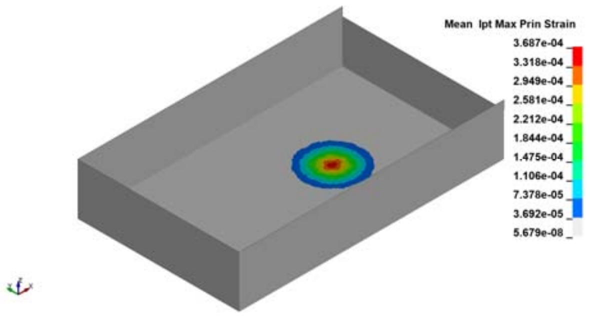


Fig. 7. The principal strain contour of the liner plate [7]

4. Conclusions

Using the load-mapping technique, this study numerically evaluated the structural integrity of the reactor cavity subjected to steam explosion loads. The numerical results indicate that the probability of concrete damage leading to reactor cavity collapse is extremely low. The liner plate and reinforcements exhibit a minimal risk of failure, as their maximum principal and tensile strains remain within acceptable limits. Based on the damage assessment, the structural integrity of the reactor cavity is expected to be maintained during a steam explosion event.

Acknowledgements

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