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A Damage Evaluation of the Reactor Cavity Subjected to an Equivalent TNT Explosion for Fuel-Coolant Interactions

Seong-Kug Ha[a*], Yeo-Hoon Yoon[b], Kyoung-Teak Lee[b], Ik-Jung Yun[a]
[a]*Korea Institute of Nuclear Safety (KINS), 62 Gwahak-ro, Yuseong-gu, Daejeon, Korea 34142*
[b]*Korea Simulation Technologies (KOSTECH), 18 Mugunghwa-ro, Ilsandong-gu, Goyang-si, Gyeonggi, Korea 10401*
[*]*Corresponding author: skha@kins.re.kr*

1. Introduction

During a severe accident, steam explosions caused by molten fuel-coolant interactions could cause severe damages to the reactor cavity, penetration piping, support structures, and major components in a containment building [1]. Radioactive materials may leak if the containment buildings are damaged by steam explosion loads [2]. Furthermore, as the reactor vessel is elevated, the pipe connections leading to it may bend, resulting in a loss of containment building leak-tightness [2]. This study conducts a preliminary numerical analysis to assess structural damages to concrete and liner plate in the reactor cavity during an equivalent TNT explosion for fuel-coolant interaction [2].

2. Finite element modeling

2.1 Material models

An auto-generated function in the KCC concrete model is used to provide all of the parameters based on the density, Poisson's ratio, and compressive strength of concrete to simulate the nonlinear characteristics of concrete material [2]. To account for the effective strain rate effect, the dynamic increase factors of concrete are implemented on a defined curve [2]. The plastic kinematic model in LS-DYNA is used to simulate the nonlinear properties of steel materials, and the Cowper and Symonds model is also used to account for the strain rate effect [2]. Details of material properties as well as dynamic increase factors for concrete, reinforcements, and liner plate can be found in Ha and Yoon [2].

2.2 FE modeling and analysis conditions

The dimensions of the reactor cavity finite element model used in this study are 18.74 m (length), 11.43 m (width), and 19.51 m (height) [2]. The concrete area is modeled with a 150-mm grid to calculate the damage caused by a steam explosion near the reactor cavity's bottom slab, and the other area is modeled with a 250-mm grid. The basemat in contact with the outer liner plate is made of 3D solid elements, and all nodes are constrained [2]. A symmetry condition is applied to the section of the basemat to simulate the continuous slab of the basemat [2].

Using an energy conversion ratio of 0.03% [2,3], the total thermal energy of the molten core can be converted into TNT-equivalent energy. The equivalent TNT mass is assumed to be 4.9 kg for this study [2,3]. It is assumed that the steam explosion occurs where the center line of the reactor pressure vessel meets the lower slab of the reactor cavity [2]. The explosive pressures in the reactor cavity are simulated by the ALE method, and then the fluid-structure interaction method in LS-DYNA is used to numerically evaluate damages of the reactor cavity [2,3].

3. Numerical results

3.1. Displacement

A front displacement is recorded at the top surface of the bottom slab near the center of the equivalent TNT explosion, while a rear displacement is measured at the lower surface of the bottom slab in the same direction as the Z-axis [2]. The maximum front and rear displacements are measured to be 13.68 mm and zero at 0.19 ms of analysis time, respectively, as shown in Fig. 1 [2]. Furthermore, the residual front and rear displacements of the bottom slab are measured to be 7.32 mm and 0.2 mm after 50.0 ms, respectively [2]. Local deformation is seen on the bottom slab based on numerical results [2].

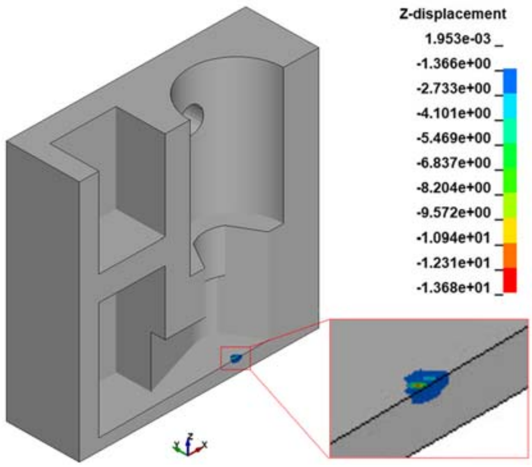

Fig. 1. Maximum front and rear displacement of the bottom slab [2]

3.2. Concrete damage

According to NEI 07-13[4], the concrete damage is assumed to exceed the 0.5 % shear strain of concrete. As depicted in Fig. 2, the maximum shear strain of the concrete is 2.00% at 0.19 ms, and only local spalling of the concrete is observed in the vicinity of the equivalent

TNT explosion region [2].

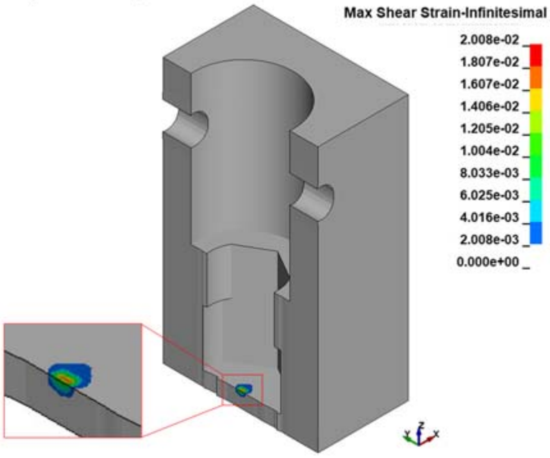

Fig. 2. Maximum shear strain of the concrete [2]

3.3. Liner plate damage

According to NEI 07-13 [4], it is assumed that failure of the liner plate proceeds when the principal strain of the membrane exceeds 5.00%. The maximum principal strain of the liner plate is predicted to be 0.057 % at 0.49 ms, which is a very small value when compared to the failure criteria, as shown in Fig. 3 [2]. It can be concluded that there is no damage to the liner plate [2].

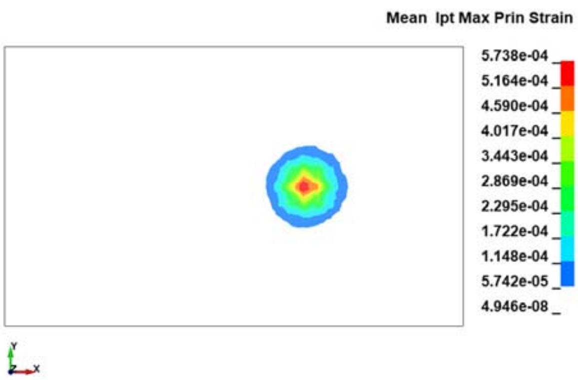

Fig. 3. Maximum principal strain of the liner plate [2]

4. Conclusions

In this study, a numerical analysis is performed to evaluate structural damage to concrete and liner plate in the reactor cavity caused by an equivalent TNT explosion. The numerical results demonstrate that the bottom slab has small deformation and local concrete spalling in vicinity to the equivalent TNT explosion location [2]. The liner plate remains undamaged because its maximum principal strain is negligible in comparison to the failure criteria [2].

Acknowledgements

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