An Overview of Recent Studies on Structural Damages of Containment Building Subjected to Steam Explosion Loads

Seong-Kug Ha[a*], Ik-Jung. Yun[a], Jong-Bum Park[a], Sang-Yun Kim[a]
[a]*Korea Institute of Nuclear Safety, 62 Gwahak-ro, Yuseong-gu, Daejeon, Korea 34142*
[*]*Corresponding author: k732hsg@kins.re.kr*

1. Introduction

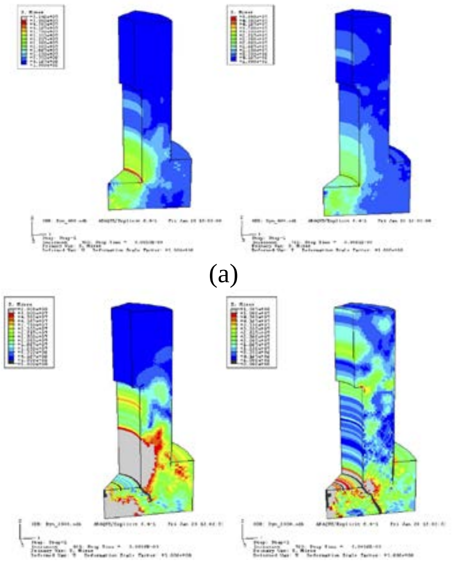
Since the TMI-2 accident, many studies have been conducted to investigate the steam explosion process and develop the code, and model to simulate the steam explosion pressures [1,2,5,6,7]. However, it is still very challenging to evaluate the structural damages of the containment buildings subjected to the steam explosion loads due to the complex shock waves, complex geometric structures, and complex mechanical behaviors of materials under dynamic loading [1].

2. An overview of recent studies

In this paper, some recent studies regarding numerical analysis to assess structural damages of the containment buildings under the steam explosion loads have been reviewed.

2.1 Cizelj et al. (2006)

Cizelj et al. carried out numerical research to estimate the steam explosion pressures and to evaluate the structural damages of the typical PWR cavity subjected to their steam explosion pressures [2]. For this, they suggested the fit-for-purpose steam explosion model based on CFD code. From CFD analysis, pre-mixture pressures of 40 MPa and 250 MPa were calculated corresponding to steam explosion case with energy conversion ratio 1% and 10%, respectively. The highest pressure loads on the cavity walls were observed with the pre-mixture high-pressure relief and propagation of pressure shock waves to the walls within the first 3~5 ms. The predicted steam explosion pressures by CFD code were transferred to ABAQUS /Explicit code to analyze the structural damages of the cavity walls. This study assumed that the damages of cavity walls would instantly occur with (tensile or compressive) hydrostatic pressure exceeding 50 MPa. From structural analyses, it was concluded that no damage was observed in the case of the pre-mixture pressure of 40 MPa, and the localized damages from the minor to medium levels were also observed in the case of the pre-mixture pressure of 250 MPa. Although there were potential localized damages of cavity walls, the entire collapse of the whole cavity was prevented for both cases.



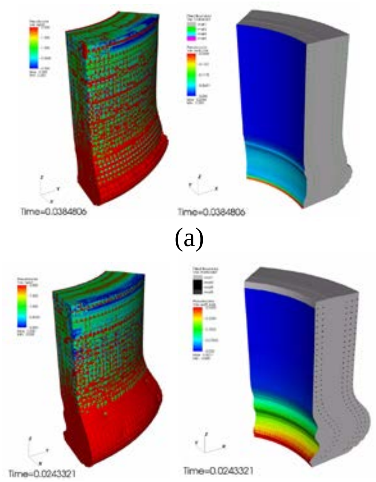
(a)

(b)

Fig. 1. The von-Mises stresses contour of the reactor cavity wall under the pre-mixture pressure of 40 MPa (a) and 250 MPa (b) [2]

2.2 Noble (2007)

Noble reported a series of numerical analyses, including finite element model assumptions for ESBWR pedestal wall and its failure criteria [3]. The report aims at determining the structural damages of the ESBWR pedestal wall subjected to steam explosion pressures. In particular, the effective plastic strain was selected as failure criteria to assess damages of the steel materials. That is, rebar and steel liner would fail when the effective plastic strain reached 20% and 30%, respectively. Total failure of the pedestal wall would occur if the concrete was fully damaged and the rebar has reached the effective plastic strain of 20%. For the 300 KPa-sec case, it was seen that concrete was fully damaged at the base of the pedestal wall, however, the damaged concrete may be confined within the rebar mat. It was also observed that peak strains of the steel liner were near 20~24% at the base of the pedestal wall. Thus, total failure of the pedestal wall may be prevented. For the 600 KPa-sec case, it was shown that concrete was extensively damaged throughout the base of the pedestal wall. It was also seen that effective plastic strains of the steel liner and all the rebar reached a level of 30% and 20% at the base of the pedestal wall. Thus, the pedestal wall would fail for the 600 KPa-sec case.



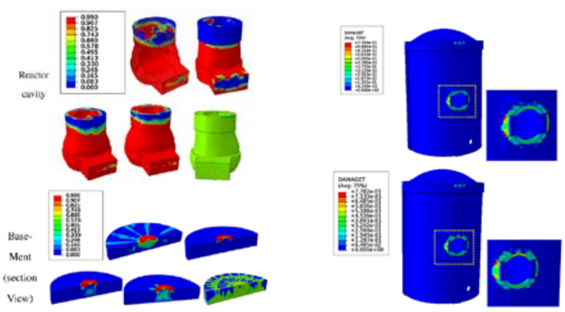
(a)

(b)

Fig. 2. Concrete damage (left) and effective plastic strain of inner steel liner (right) of the cavity wall for the 300 KPa-sec case (a) and the 600 KPa-sec case (b) [3].

2.3 Chunyu et al. (2014)

Chunyu et al. conducted a series of numerical studies to assess the structural damages of a whole containment building of the CPR1000 subjected to steam explosion loads [1]. For this, the dynamic response and the possible damages of the CPR1000 PWR containment were analyzed and discussed. In particular, a scalar damage parameter, *d* in the concrete damaged plasticity model was chosen to determine the damage and failure of the CPR1000 containment building, where $d = 0$ indicates no damage and d=1 means complete failure. It was shown that both the reactor cavity and the baseboards were severely damaged, however, the basement was partially damaged. It was seen that significant deformations were observed with the pressure vessel and the pipelines so that most of the blast energy was absorbed by the deformation of the facilities and the internal components. No damage to the penetration part of the containment wall was observed since an only small fraction of blast energy was transferred to the containment. Finally, the structural integrity of the containment wall can be ensured.

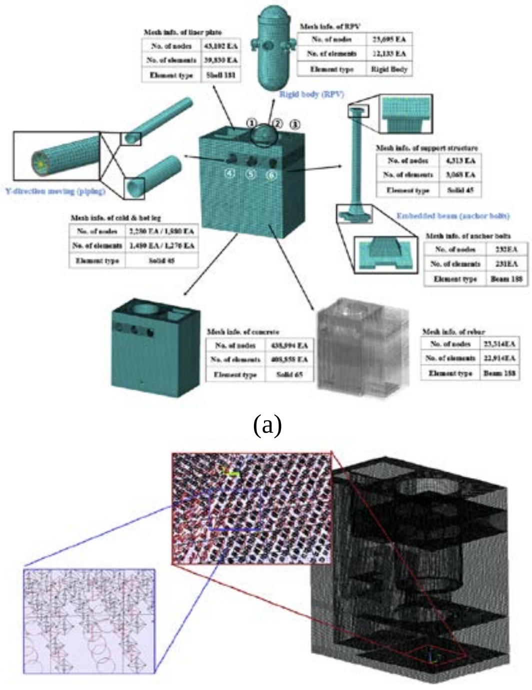


(a) (b)

Fig. 3 Damage of the reactor cavity (a) and containment wall (b) affected by steam explosion loads [1]

2.4 Kim et al. (2015)

Kim et al. performed primarily numerical analyses to evaluate structural response and damages of the reactor cavity under various steam explosion conditions [4]. For this, a combined numerical approach with CFD analysis and FE analysis was carried out to predict the steam explosion pressure loads. From CFD analysis, the maximum steam explosion pressures of the side vessel failure mode were much higher than those of the bottom vessel failure mode. For subsequent FE analysis, the reactor cavity, reactor pressure vessel, penetration piping, and support structures were considered and numerically modeled. It was shown from FE analysis that the maximum stresses of rebar were higher than the corresponding yield strength, whereas the maximum stresses of the concrete were sufficiently lower than its yield strength. Small vertical displacements of major components were observed compared to their overall dimensions. It was concluded that there were potential minor or medium local damages of the reactor cavity, however, the structural integrity of the reactor cavity was maintained under the steam explosion conditions.



(a)

(b)

Fig. 2. Combined FE models (a) and damages of concrete for the reactor cavity (b) [4]

3. Conclusions

Up to date, several finite element analyses have been carried out to evaluate the structural damages and response of the containment buildings under steam explosion conditions. Overall, various structural failure criteria were chosen to determine the structural damages of the containment buildings subjected to the steam explosion loads. Further, the detailed discussion needs to determine proper structural failure criteria for structural integrity assessment of the containment buildings under steam explosion conditions.

ACKNOWLEDGEMENT

This work was supported by the Nuclear Safety Research Program through the Korea Foundation Of Nuclear Safety (KoFONS) using the financial resource granted by the Nuclear Safety and Security Commission (NSSC) of the Republic of Korea (No. 2106008) .

REFERENCES

[1] Z. Chunyu, C.P. Zhang, J. Lin, J. Liu, Y. Zhang, S.W. Biaoa, Evaluation of the structural integrity of the CPR1000 PWRcontainment under steam explosion accidents, Nuclear Engineering and Design, Vol. 278, p. 632–643, 2014.

[2] L. Cizelj, B. Koncar, M. Leskovar, Vulnerability of a partially flooded PWR reactor cavity to a steam explosion, Joef Stefan Institute, Nuclear Engineering and Design, Vol. 236, p.1617–1627, 2006.

[3] C. R. Noble, DYNA3D Finite Element Analysis of Steam Explosion Loads on a Pedestal Wall Design, UCRL-TR-227386, January 22, 2007.

[4] S.H. Kim, Y.S. Chang, S.C. Song, Y.J. Cho, Structural assessment of fully flooded reactor cavity and penetration piping under steam explosion condition, International Journal of Pressure Vessels and Piping, Vol. 131, p. 36-44, 2015.

[5] M.L. Corradini, B.J. Kim, M.D. Oh, Vapor explosions in light water reactors. A review of theory and modelling. Progress Nuclear Energy Vol. 22, p. 1–117, 1988.

[6] P. Piluso, G. Trillon, D. Magallon, Material effect and steam explosion at high temperature (T>2300 K), International Journal of Thermophysics, Vol. 26, p.1095–1114, 2005.

[7] R. Meignen, S. Picchi, MC3D Version 3.5: User's Guide. IRSN Report, NT/DSR/SAGR/05-84, 2005.