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Effects of Anchor Bolts Failures in Steam Explosion Analyses

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1. Introduction

Steam explosion may occur in a nuclear power plant by molten core-coolant interactions when the external reactor vessel cooling strategy is failed. This phenomenon can threat the integrity of reactor cavity, penetration piping and support structures [1]. Even though extensive researches have been performed to predict influences of the steam explosion, due to complexity of physical phenomena and environmental thermal hydraulic conditions, it is remained as one of possible hazards. A steam explosion can cause intensive and rapid heat transfer, and lead to the formation of pressure waves and production of missiles that may endanger surrounding reactor cavity wall and associate components due to resulting dynamic effects [2]. The goal of this research is to examine structural integrity of RPV (Reactor Pressure Vessel) support structures and anchor bolts under typical ex-vessel steam explosion conditions through FE analyses. Particularly, influence due to the failure of anchor bolts connecting RPV and support structures was evaluated.

2. Numerical Analysis

2.1 Pressure Histories

The analysis method of the steam expansion phase, adopted in this research, is based on the Hicks-Menzies thermodynamic approach taking into account the microinteraction zone concept [1]. It was assumed that the heat transfer from the molten core to the coolant was completed during the preceding three steam explosion phases. Due to the assumption of the adiabatic vapor expansion, the density of the mixture during the expansion process can be calculated solely as a function of pressure [2]:

$$\rho_{2\to3}^{mix}(p) = \frac{\rho_2^{mix}}{(1-\alpha_2^{vap}) + \frac{\alpha_2^{vap}\rho_2^{vap}}{\rho_{2\to3}^{mix}(p)}} = \frac{\rho_2^{mix}}{1+\alpha_2^{vap}\left(\left(\frac{p_2}{p}\right)^{\frac{1}{\kappa}}-1\right)}$$

where ρ_2^{mix} is the mixture density at the start of the expansion phase and $\rho_{2\to3}^{vap}$ is the vapor density during the expansion phase. So, the behaviors of the molten core mixture as well as liquid and air state coolant were analyzed by a CFD code [3].

2.2 FE Model

FE models consist of RPV, support structure and anchor bolts. The RPV FE model was generated by employing 4 node solid elements consists of 23,695 nodes and 12,133 elements. The RPV support structures were modeled by using 8 node solid elements with 4,313 nodes and 3,068 elements. 12 bottom anchor bolts and 14 upper anchor bolts per each support were modeled by 4 node beam elements with equivalent diameter [2]. Fig 2 represents combined FE model and location of anchor bolts.

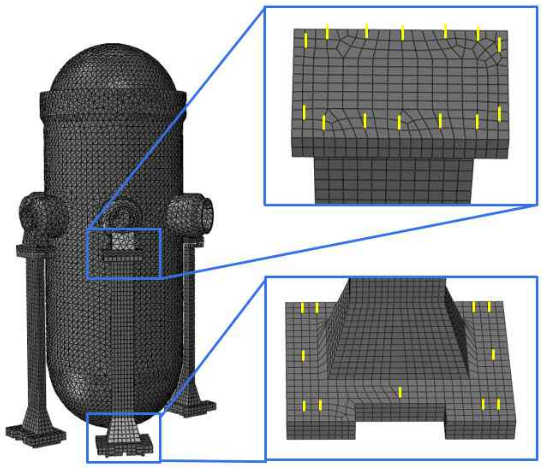


Fig. 1 Combined FE mode and location of anchor bolts

2.3 Analysis Conditions

Stress analyses of the RPV, support structure and anchor bolts were performed by using commercial FEM code. Table I summarizes the material properties used in the structural assessment. As boundary condition, bottom anchor bolts connecting reactor cavity and RPV support structures were fully fixed. Loading conditions were set based on pressure histories of RPV lower plenum according to steam explosion condition. Pressure histories obtained from the previous study [3] and gravity were applied to RPV as input loading.

With regard to analysis cases, two kinds of vessel failure modes such as BVF (Bottom Vessel Failure) and SVF (Side Vessel Failure) were considered [4]. Also, influence due to the failure of upper anchor bolts connecting RPV and support structures was evaluated.

Table I: Material properties

Material		Modulus of elasticity (GPa)	Poisson's ratio	Yield strength (MPa)	Ultimate tensile strength (MPa)
RPV	SA508 Gr.3	212.26	0.3	375.91	609.70
Support structure	SA506 Gr.1A	199.95	0.3	413.68	650.52
Anchor bolt	SA540 Gr.B23	199.95	0.3	1061.8	1179

3. Analysis Results

3.1 Stress Evaluation

Table II compares maximum von Mises stresses of the RPV, support structures and anchor bolts, respectively. The resulting stresses were high under SVF conditions from the failure mode point of view. With regard to failure of anchor bolts, the resulting stresses were high under non failure condition due to fixed component. However, all stress values did not exceed their yield strengths. Each stress acting on the components was ranged from 75MPa to 272MPa, approximately, so that belonged to elastic regime.

Table II: Maximum stresses of RPV, supports and anchor bolts

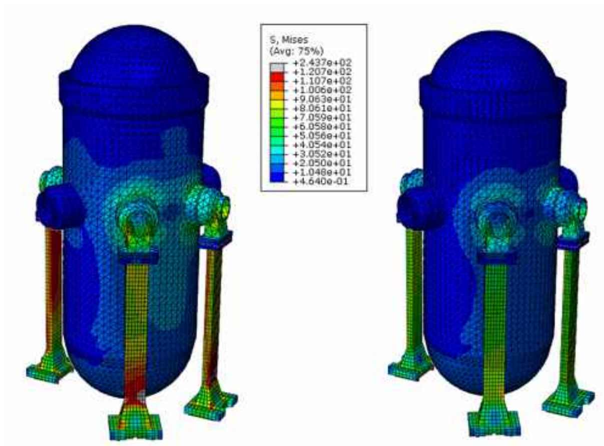
Anchor bolt failure	Failure mode	Max. stress(MPa) @ RPV	Max. stress(MPa) @ support	Max. stress(MPa) @ anchor bolts
Non-failure	BVF	105.54	219.21	180.67
	SVF	185.42	272.87	245.12
Failure	BVF	99.08	105.23	75.87
	SVF	180.08	198.87	166.12

3.2 Displacement Evaluation

Table III summarizes the maximum y-directional displacements of the RPV and hot leg, respectively. While the vertical movement of RPV under anchor bolt failure was higher than non-failure, the resulting displacement was small comparing to the overall dimensions of the RPV. With regard to the hot legs, despite of their relatively complex trends, the vertical movements were also minimal and the hot legs was unlikely to be affected by the steam explosion.

Table III: Maximum displacement of RPV and piping

Anchor bolt failure	Failure mode	Max. displacement (mm) @ RPV	Max. displacement (mm) @ hot leg	
			A	B
Non-failure	BVF	1.12	0.81	0.82
	SVF	4.15	3.89	3.85
Failure	BVF	3.02	2.51	2.52
	SVF	7.89	6.85	6.86



(a) Non-failure (b) Anchor bolt failure

Fig. 2 Stress contours at 0.002 sec (SVF)

4. Conclusion

In this paper, influence of RPV and support structure due to the anchor bolt failure were evaluated under typical steam explosion conditions and the following conclusions were derived.

(1) The highest maximum stresses were calculated at the support structures under the steam explosion condition with the SVF and anchor bolts non-failure. The all stress values did not exceed their yield strengths.

(2) The displacements were high under anchor bolt failure conditions. However, the vertical movements of major components were small comparing to the overall dimensions of them.

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