A Study on Reinforced Concrete Cracking Models for Steam Explosion Analysis

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1. Introduction

In order to mitigate hypothetical severe accident scenarios in an advanced light water reactor, either a core catcher is placed or an ERVC(External Reactor Vessel Cooling) strategy is adopted during design stage. However, when molten core penetrates RPV(Reactor Pressure Vessel) lower plenum and contacts with water in the reactor cavity, serious structural damage may occur. 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[1, 2]. The goal of this research is to examine load carrying capacity of the reactor cavity as a barrier under typical ex-vessel steam explosion conditions through a series of numerical analyses. Particularly, influences of cracking models are compared with regard to the reinforced concrete structure by taking into account the RPV, primary system piping and supports.

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:

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

where ρ_2^{mix} is the mixture density at the start of the expansion phase and $\rho^{vap}{}_{2\to3}$ 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 Analysis model

FE model consist of concrete cavity, liner plate, rebar, pipe, RPV, RPV support structure and anchor bolts. The combined model was modeled by employing 8 node 3D concrete elements, 8 node 3D solid elements, 4 node shell elements and 2 node beam elements consist of 537,736 nodes and 489,622 elements[4].

2.3 Analysis conditions

Stress analyses of the reactor cavity were performed by using Civil FEM code[5]. Table I summarizes the material properties used in the structural integrity evaluation. As boundary condition, bottom sides of the reactor cavity were fully fixed, and the cold leg and hot leg pipes were also fixed along x- and y-directions.

Two kinds of vessel failure modes such as BVF(Bottom Vessel Failure) and SVF(Side Vessel Failure) were considered[6]. Also, as the steam explosion locations, middle and bottom of the reactor cavity were considered in case of the SVF[7]. Pressure histories obtained from the CFD analysis were applied as loading conditions.

Table I: Material Properties

Material		Modulus of elasticity (GPa)	Poisson's ratio	Yield strength (MPa)	Ultimate tensile strength (MPa)
Concrete		30.44	0.2	*41.32	
Steel liner plate	SA516 Gr.60	199.95	0.3	303.36	455.0
Rebar	ASTM A615 Gr.60	199.95	0.3	468.84	620.5
Anchor bolt	SA-540 Gr.B23	199.95	0.3	1061.8	1179
Pipe and RPV support	SA-506 Gr.1A	199.95	0.3	413.68	650.52

[Note] *: Compressive strength

2.4 Concrete cracking models

The Willam-Warnke cracking model was employed to predict failure of concrete materials. The ultimate tensile strength and compressive strength are needed to define a failure surface for the concrete. Consequently, a criterion for failure of the concrete due to a multiaxial stress state can be calculated. In a concrete element, cracking occurs when the principal tensile stress in any direction lies outside the failure surface. After cracking, the elastic modulus of the concrete element is set to zero in the direction parallel to the principal tensile stress direction. Crushing occurs when all principal stresses are compressive and lie outside the failure surface; subsequently, the elastic modulus is set to zero in all directions, and the element effectively disappears.

The Winfrith concrete cracking model was also considered, which is premised upon cracking, crushing and shear retention depending on crack width and aggregate size. In this model, the calculation of rebar stresses is separated from the calculation of concrete stresses and the two components are smeared together according to their relative cross-sectional areas to form the total element stresses. According to the model, the material behaves plastically as a result of failure in compression, but up to three orthogonal cracks can be formed due to tensile stress is allowed to decay as linear function of crack normal extension[4].

3. Analysis results

3.1 Stress results

Tables II compares maximum von Mises stresses of the reinforced concrete and anchor bolts, respectively. The resulting stresses were high under SVF conditions from the failure mode point of view However, the difference according to the explosion locations was not significant. The maximum stress at the rebar under the SVF conditions exceeded its yield strength but less than ultimate tensile strength. The maximum stresses acting on the anchor bolts were ranged from 75MPa to 168MPa, approximately, so that belonged to elastic regime.

Table II: Maximum Stresses of Reinforced Concrete

Failure mode-Explosion location	Max. stress(MPa) @ concrete	Max. stress(MPa) @ rebar	Max. stress(MPa) @ anchor bolts
BVF-Bottom	5.74	319.21	75.87
SVF-Bottom	9.08	556.87	166.12
SVF-Middle	9.21	559.12	167.50

3.2 Cracking results

Even though cracking and crushing occurred by the steam explosion, reinforced concrete was not penetrated regardless of failure modes and cracking models. Figs. 2 and 3 compare damaged regions in the cavity analyzed for the SVF-Middle failure mode with two concrete cracking models, as typical cases. On the whole, damaged concrete thicknesses predicted by the Willam-Warnke model were about 10% larger than those by the Winfrith crack model. Also, damaged regions due to cracking and crushing predicted by the Willam-Warnke model were wider than those by the Winfrith model.

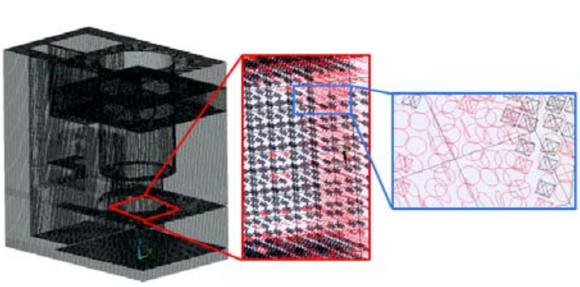

Fig. 2 Damaged region in the cavity
(SVF-Middle mode, Willam-Warnke cracking model)

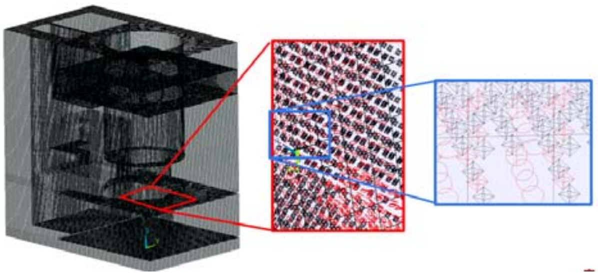

Fig. 3 Damaged region in the cavity
(SVF-Middle mode, Winfrith cracking model)

4. Conclusion

In this paper, systematic numerical analyses of the reactor cavity, RPV, main pipes and supports were carried out under typical steam explosion scenarios and the following conclusions were derived.

(1) The resulting stresses were high under the failure mode of SVF and the explosion location of middle although the difference according to the explosion locations was not significant.

(2) The maximum stresses at the concrete were sufficiently lower than its yield strength but the maximum stresses at the rebar under the SVF conditions exceeded its yield strength.

(3) The cracking analysis results revealed that damaged regions predicted by the Willam-Warnke model were wider than those by the Winfrith model.

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