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Effect of Multi-Layered Corium Formations on Integrity of Steel Components under Steam Explosion Condition

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1. Introduction

Steam explosion may occur in nuclear power plants due to molten fuel-coolant interaction when the ERVC (External Reactor Vessel Cooling) strategy fails[1,2]. This phenomenon can threat the integrity of reactor cavity, penetration piping and support structures as well as major components. Even though extensive researches have been performed to predict the influence of the steam explosion, it remains to be one of possible hazards due to complexity of physical phenomena and harsh environmental thermal-hydraulic conditions.

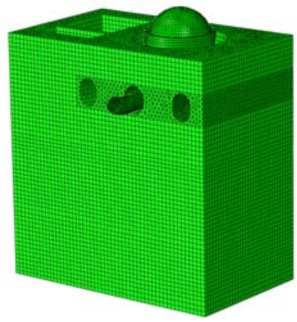
The object of the present study is to examine effect of multi-layered corium formations on the integrity of steel components under a representative steam explosion condition. In this context, multi-layered corium formation conditions are assumed based on a previous study[3]. Subsequently, stress evaluation of steel components is performed by TNT (trinitrotoluene) model for the steam explosion analysis and their results are discussed.

2. Numerical Analysis

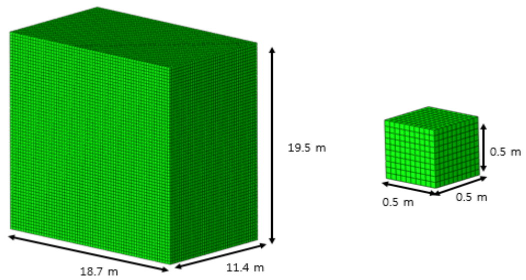
2.1 FE model

Fig. 1(a) and Table I represent the FE model of structures and mesh information used for the steam explosion analyses. The steel liner plate was modeled by employing shell elements and merged with the concrete. The vertical and horizontal rebar embedded in the concrete were modeled by using beam elements. The explosive material has been modeled by using the Eulerian modeling technique. Figs. 1(b) and (c) show a typical FE mesh of air and explosive regions. These regions were generated by Eulerian continuum three dimensional eight node reduced integration elements (EC3D8R) in ABAQUS element library[4].

Eulerian elements are necessary to efficiently propagate the explosion wave through air. The Eulerian and Lagrangian elements used for air and explosive regions interacting with the reactor cavity and steel components were simulate by taking general contact option[5]. The pressure-volume relation of the explosive region has been simulated by using Jones Wilkins Lee Equation-Of-State (JWL EOS) in the TNT model.



(a) Reactor cavity and steel components



(b) Air region (c) Explosive region

Fig. 1 FE model and mesh used in analysis

Table I: Information of mesh

Component	No. of nodes	No. of elements	Element type
Concrete	438,994	408,858	8-node 3D element
Liner plate	10,044	7,466	4-node shell element
Rebar	23,314	22,914	3-node beam element
RPV	23,695	12,133	8-node 3D element
Pipes	2,280	1,980	8-node 3D element
Support structure	4,313	3,068	8-node 3D element
Anchor bolts	1,244	1,124	3-node beam element
Air	162,162	153,140	Eulerian 8-node 3D element
Explosive	1,331	1,000	Eulerian 8-node 3D element

2.2 Analysis conditions

A representative accident scenario was set to examine effect of multi-layered corium formations relating to the steam explosion. In due sequence, at first, molten pool is formed in the lower plenum. Secondly, when coolant for ERVC is injected, the reactor cavity is fully flooded. Subsequently, as the molten corium penetrates the lower plenum of RPV, it reacts to the coolant in the reactor cavity. Finally, due to failure of IVR-ERVC strategy, the steam explosion occurs.

Three analysis conditions were selected to examine effect of multi-layered corium formations as summarized in Table II. Only SVF (Side Vessel Failure) failure mode was considered in relation to focusing effect. As the corium formation, two kinds of multi-layer configuration were assumed like 2 and 3 layers, and compared to the previous result[6] without corium formation at room temperature. RPV temperature of 360℃ and thermal stress of 20.2 MPa were considered in the case of 2-layer and RPV temperature of 450℃ and thermal stress of 35.5 MPa were taken into account in the case of 3-layer, respectively. Temperatures of other steel components were set to 130℃ and material properties used in the analysis were determined in accordance with these temperatures.

Table II: Analysis conditions

Case	Failure mode	Corium formation	Steel component temperature		Thermal stress
1	SVF	None	Room temperature		None
2		2-layer	RPV	360℃	20.2 MPa
			Other steel components	130℃	
3		3-layer	RPV	450℃	35.5 MPa
			Other steel components	130℃	

3. Analysis Results

Fig. 2 represents the von Mises stress distribution of reactor cavity and steel components after the steam explosion, representatively. The stresses were high at RPV from the corium formation point of view. The maximum stress also occurred at the side of RPV lower plenum that is the explosion location. Table III compares the maximum von Mises stresses and distribution of the RPV, pipes, support structure and anchor bolts. The RPV and anchor bolts defined as the components having the highest and lowest stresses in all cases. However, maximum stresses at steel components were sufficiently lower than their yield strengths. On the other hand, effect of corium formation was the highest at Case 3. Difference of von Mises stresses between Case 2 and Case 3 was 16%, approximately.

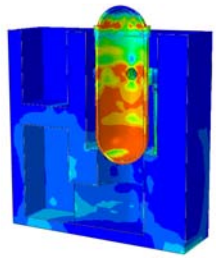


Fig. 2 von Mises stress distribution (Case 3)

Table III: Maximum von Mises stresses of steel components

Case	Max. von Mises stress (MPa) @RPV	Max. von Mises stress (MPa) @pipes	Max. von Mises stress (MPa) @support structure	Max. von Mises stress (MPa) @anchor bolts
1	266.74	250.81	245.57	235.34
2	287.45	271.02	255.54	245.89
3	332.54	296.22	280.48	270.56

4. Conclusion

In this paper, comparative numerical analyses were carried out to examine effect of the multi-layered corium formations on integrity of steel components under a typical steam explosion condition and the following conclusions were derived.

(1) The highest maximum von Mises stress was calculated at RPV. However, stress values of all components did not exceed their yield strengths.

(2) Effect of the 3-layer corium formation was higher than 2-layer corium formation. Resulting von Mises stress increased 20% than that of no corium formation and 16% than that of 2-layer corium formation.

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