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Original Article

Modeling of Reinforced Concrete for Reactor Cavity Analysis under Energetic Steam Explosion Condition

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ABSTRACT

Background: Steam explosions may occur in nuclear power plants by molten fuel–coolant interactions when the external reactor vessel cooling strategy fails. Since this phenomenon can threaten structural barriers as well as major components, extensive integrity assessment research is necessary to ensure their safety.

Method: In this study, the influence of yield criteria was investigated to predict the failure of a reactor cavity under a typical postulated condition through detailed parametric finite element analyses. Further analyses using a geometrically simplified equivalent model with homogeneous concrete properties were also performed to examine its effectiveness as an alternative to the detailed reinforcement concrete model.

Results: By comparing finite element analysis results such as cracking, crushing, stresses, and displacements, the Willam–Warnke model was derived for practical use, and failure criteria applicable to the reactor cavity under the severe accident condition were discussed.

Conclusion: It was proved that the reactor cavity sustained its intended function as a barrier to avoid release of radioactive materials, irrespective of the different yield criteria that were adopted. In addition, from a conservative viewpoint, it seems possible to employ the simplified equivalent model to determine the damage extent and weakest points during the preliminary evaluation stage.

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1. Introduction

Steam explosions may occur in nuclear power plants due to molten fuel–coolant interactions when the external reactor vessel cooling strategy [1,2] fails. This phenomenon can threaten the integrity of the reactor cavity, penetration piping, and support structures as well as major components. Even though extensive research has been performed to predict the effects of steam explosions, it remains a possible hazard due to the complexity of physical phenomena and harsh environmental thermal–hydraulic conditions [3,4].

The steam explosion phenomenon is usually classified into four phases: premixing, triggering, propagation, and expansion processes [5,6]. At first, in the premixing phase, the

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molten jet breaks up, and a coarsely mixed region of molten corium and coolant is formed. The explosive system can remain in this metastable state until the melt is quenched or a steam explosion is triggered. The triggering event is a disturbance that destabilizes the vapor film around a melt particle, allowing liquid–liquid contact and leading to locally enhanced heat transfer, pressurization, and fine fragmentation. During the propagation phase, an escalation process takes place resulting from heat transfer after the triggering event. Finally, during the expansion phase, thermal energy of the coolant is converted into mechanical energy so that the high-pressured mixture countered by the inertial constraints governs the possibility of a steam explosion. If the localized high pressure is quickly stabilized, only the kinetic energy transmitted to materials around the interaction zone becomes the unique damaging agent [3].

To resolve the remaining open issues on the fuel–coolant interaction) processes and their effects on steam explosion energetics, the IFCI [7] and TEXAS [8] analysis codes were developed. In addition, the OECD project of Steam Explosion REsolution for Nuclear Applications (SERENA), consisting of experimental and analytical parts, was launched in 2007 to enhance the understanding and modeling techniques of the fuel–coolant interaction key features [3,9]. However, despite these previous researches, structural evaluation methods and criteria for steam explosions were not clearly defined for reactor applications. Structural evaluation requires appropriate models either to delineate complicated reinforced concrete material behaviors or to reduce computational cost during the initial design stage.

In this context, the present numerical study focuses on the yield criteria under a typical postulated steam explosion condition. The influence of yield criteria are investigated through parametric finite element (FE) analyses, and subsequent structural assessments are also performed for the reactor cavity in a nuclear power plant with an electric power capacity of 1,400 MWe. Moreover, to examine the effectiveness of an alternative to the detailed reinforcement model, simplified FE analyses with homogeneous concrete properties are carried out and their results, such as cracking, crushing, stresses, and displacements, are compared with each other in detail.

2. Theory of concrete structural evaluation

2.1. Yield criteria of concrete material

Even though various material models have been proposed for concrete structural analyses, four representative yield criteria, Wiliam-Warnke (WW) [10], Mohr-Coulomb (MC) [11], Drucker-Prager (DP) [12], Winfrith (W) [13], were examined in this study. All the governing equations to define yield criteria can be represented by the stress tensor that is closely related to the following stress invariants (I_i; i = 1, 2, and 3) and deviatoric stress invariants (J_i; i = 1, 2, and 3):

$$I_1 = \sigma_{11} + \sigma_{22} + \sigma_{33}$$

$$I_2 = \sigma_{11}\sigma_{22} + \sigma_{22}\sigma_{33} + \sigma_{33}\sigma_{11} - \sigma_{12}^2 - \sigma_{23}^2 - \sigma_{31}^2 \quad (1)$$

$$I_3 = \sigma_{11}\sigma_{22}\sigma_{33} + 2\sigma_{12}\sigma_{23}\sigma_{31} - \sigma_{12}^2\sigma_{33} - \sigma_{23}^2\sigma_{11} - \sigma_{31}^2\sigma_{22}$$

$$J_1 = S_{11} + S_{22} + S_{33}$$

$$J_2 = \frac{1}{3}I_1 - I_2 \quad (2)$$

$$J_3 = \frac{2}{27}I_1^3 - \frac{1}{3}I_1 I_2 + I_3$$

Historically, the Willam–Warnke model has been adopted to predict failures of concrete and cohesive–frictional materials such as rock and soil, the yield criterion of which can be defined as a functional form:

$$f(I_1, J_2, J_3) = 0 \quad (3)$$

If the details of the second and third deviatoric stress invariants (J_2 and J_3) as well as the first stress invariant (I_1) are provided, the yield surface of the Willam–Warnke yield criterion can be specified as follows:

$$f = \sqrt{J_2} + \lambda(J_2, J_3)\left(\frac{I_1}{3} - B\right) = 0 \quad (4)$$

where λ is a function of J_2 and J_3, and B is the hydrostatic stress parameter dependent on material properties and friction angle. This model may be interpretable as a combination of the Mohr–Coulomb and Drucker–Prager yield criteria.

The Mohr–Coulomb yield criterion was developed to deal with the response of concrete in which compressive loads are prevailing. It has been reported that this model leads to a relatively accurate prediction, and its yield surface can be expressed as follows [11]:

$$f(I_1, J_2, \theta) = \frac{1}{3}I_1\sin\phi + \sqrt{J_2}\sin\left(\theta + \frac{\pi}{3}\right) + \frac{\sqrt{J_2}}{\sqrt{3}}\cos\left(\theta + \frac{\pi}{3}\right)\sin\phi - c\cos\phi \quad (5)$$

where ϕ and c are material parameters, and θ is the stress state parameter dependent on the deviatoric stress invariants.

$$\theta = \frac{1}{3}\mathrm{acos}\left(\frac{3\sqrt{3}}{2}\frac{J_3}{J_2^{3/2}}\right) \quad (6)$$

Eqs. (5) and (6) represent straight lines, as the yield surface of the Mohr–Coulomb yield criterion has an irregular hexagonal shape, which is enveloped by the smooth yield surface of the Drucker–Prager model.

The Drucker–Prager yield criterion [12] describes the response of concrete subjected to compression moderately well and provides a smooth yield surface. This model defines the yield surface as a function of material parameters α and y:

$$\sqrt{J_2} + \alpha I_1 + y = 0. \quad (7)$$

$$\alpha = \frac{2\sin\phi}{\sqrt{3}(3 - \sin\phi)}, \quad y = \frac{6\cos\phi}{\sqrt{3}(3 - \sin\phi)}. \quad (8)$$

where ϕ is the friction angle between 30° and 37°, approximately, which can be determined by experimental data. In the present study, the value of the friction angle was set to 37° conservatively.

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