

Finite Element Analysis and Simplified Modeling of RPV Lower Head Penetration Failure

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1. Introduction

According to the OECD lower head failure (OLHF) tests [1], it was observed that failure of the reactor pressure vessel (RPV) lower head can occur at the penetration weld, and this takes place earlier than in the case without penetrations. The results highlight the importance of assessing failure at the penetration.

Several studies have investigated penetration failure assessment. For example, Chavez and Rempe analyzed the thermal response of the lower head vessel and penetration using finite element analysis [2]. Oh et al. conducted finite element analysis along with experiments on the thermo-mechanical response of the penetration [3]. Amidu et al. performed three-dimensional thermal analysis at the penetration [4]. An et al. carried out experiments on the thermal failure of the penetration [5].

The main objectives of this study are twofold. First, we aim to understand the penetration weld failure mechanism through detailed analysis using the finite element method. Second, we apply the existing crack model to assess the weld failure and evaluate its accuracy against the finite element analysis result.

2. Finite Element Analysis

The open-source finite element analysis software Code-Aster is employed in this study. Three geometrical models are considered: a three-dimensional (3D) model, a two-dimensional axisymmetric (2D) model, and a two-dimensional axisymmetric local (2D-L) model, as shown in Fig. 1. The 3D and 2D models consist of (1) the penetration, (2) the local region of the vessel wall near the penetration, (3) the weld, and (4) the surrounding vessel wall. The 2D-L model, in contrast, excludes the surrounding vessel wall and is restricted to the adjacent region of the penetration. Therefore, an appropriate boundary condition must be identified for the 2D-L model so that its results are consistent with those of the 3D (or 2D) model. This comparison forms the basis for conceptualizing a simplified model of the penetration failure.

Fig. 2 compares the equivalent strain at the singular tip of the gap between the penetration and the vessel wall. The 2D-L model agrees with the 3D and 2D models when the appropriate boundary condition, including hoop stress, is applied. This indicates that the hoop stress, rather than the internal pressure, is a critical factor

governing penetration failure. Oh et al. also reached at a similar conclusion [3].

The finite element analysis could obtain converged solutions until the equivalent strain reaches 0.1 (at time 186 min), after which the numerical solution diverges due to the significant deformation at the singular tip. This is consistent with the experimental observation which reports leakages at 194 min.

3. Simplified Modeling

Based on the finite element analysis results, which indicate that hoop stress is the main contributor to penetration weld failure, we propose a simplified model for penetration failure using the crack model, as shown in Fig. 3. For the stress intensity factor, we adopt the edge-crack in a semi-infinite plate, given by

$$K_I = 1.12\sigma\sqrt{\pi a} \quad (1)$$

where σ is the hoop stress and a is the length of the gap between the penetration and vessel wall as shown in Fig. 3.

Fig. 4 presents the results of the simplified model and the 2D finite element analysis. As for the constitutive relationship, elastic and elasto-visco-plastic creep models are used. It can be observed that the penetration failure is raised by the creep deformation.

The simplified model predicts earlier onset of the creep deformation, while the deformation rate is slower than the finite element analysis result. The simplified model predicts the equivalent strain of 0.1 at 190 min, which is close to the experimental result.

4. Conclusions

In this study, we investigated the penetration weld failure mechanism using finite element analysis. The results suggest that penetration weld failure is driven by creep deformation induced by hoop stress, and it occurs when the equivalent strain at the singular tip reaches approximately 0.1. Based on these observations, we developed a simplified crack-based model. The simplified model predicts similar growth of the equivalent strain at the singular tip, although the onset time of creep deformation and the creep rate differ from the finite element analysis results. Nevertheless, both the finite element analysis and the simplified model predict similar failure times, which are consistent with experimental observations.

It should be noted that, in practice, multiple penetrations are located at the reactor pressure vessel lower head, and their interactions could influence the deformation characteristics. The present study, however, is restricted to a single penetration condition. Further work is therefore required to extend the analysis and assess the effects of penetration interactions.

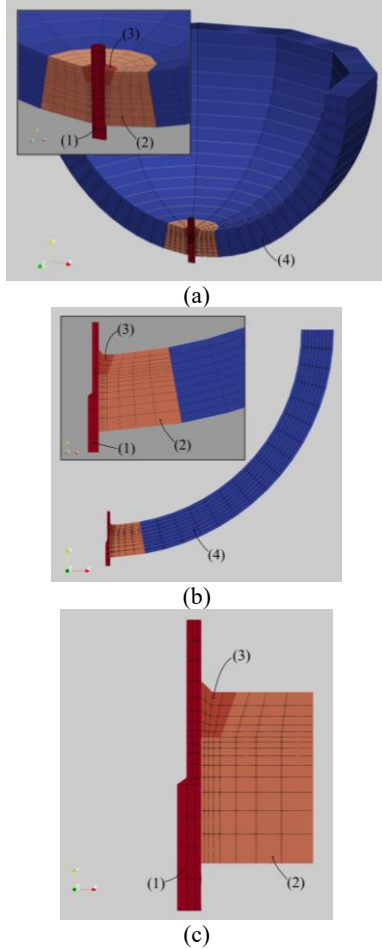


Fig. 1. Geometrical models used in the finite element analysis: (a) three-dimensional, (b) two-dimensional axisymmetric, and (c) two-dimensional axisymmetric local models.

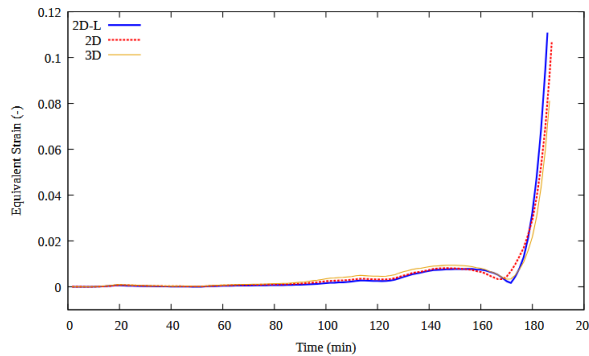


Fig. 2. Finite element analysis results of the equivalent strain at the weld.

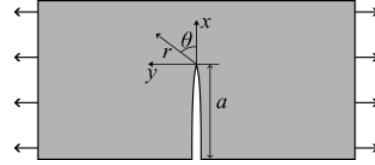


Fig. 3. Simplified modeling of the penetration failure based on the crack model.

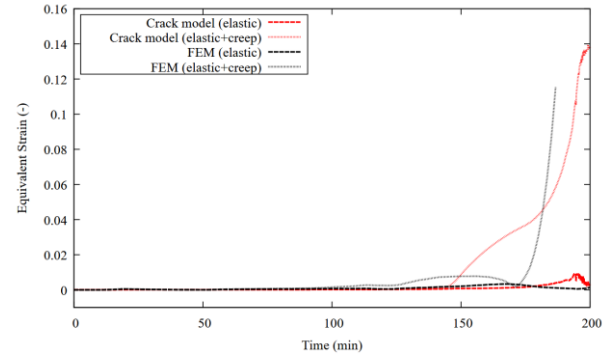


Fig. 4. Finite element analysis and crack model results of the equivalent strain at the weld.

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