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A Comparative Study on Geometry Effects of Small Modular Reactor Vessel for Nozzle Corner Crack Analysis

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1. Introduction

Reactor vessel (RV) is a critical component of nuclear power plants (NPPs) that serves as a barrier to radioactive materials. Requirements of ASME BPVC Sec. XI, App. G [1] were applied to prevent brittle fracture of RV under high-temperature and high-pressure conditions. The U.S. Nuclear Regulatory Commission released Regulatory Issue Summary 2014 [2] to require consideration of geometric discontinuities, such as nozzles, in addition to beltline assessment, due to their possibility of reducing allowable pressure.

One of small modular reactors recently under development in the Republic of Korea, called i-SMR, adopts a different RV geometry compared to large NPPs. A discontinuity region, known as transition region has been introduced between nozzle and beltline. Since the transition region is newly introduced, research on nozzle assessment with consideration of its geometric effects is insufficient.

In this study, finite element (FE) models with different RV geometries were constructed and geometric effects on nozzle cracks were investigated. For upper corner and lower corner cracks, stress intensity factors (SIFs) resulting from pressure (K_{Ip}) and thermal loading (K_{It}) were calculated. Additionally, based on calculated SIFs, pressure-temperature (P-T) limit curves for the nozzle were derived. By comparing the results, geometric effects on nozzle crack behavior were evaluated.

2. Analysis method

2.1 Analysis models

Four half-symmetric FE models were constructed using the commercial software ABAQUS [3], as shown in Fig. 1. The nozzle model with transition region (WT) was based on geometry of the i-SMR. The nozzle model without transition region (WOT) had geometry corresponding to conventional large RVs, with its radius equal to that above the transition region of WT. The nozzle corner cracks were generated based on ASME BPVC Sec. XI, App. G. The upper nozzle crack (UNC) and the lower nozzle crack (LNC), with a depth of 1/4 of the nozzle corner thickness, were constructed at the nozzle corners.

In order to obtain an accurate three-dimensional stress field, 20-node brick elements (C3D20R) were employed.

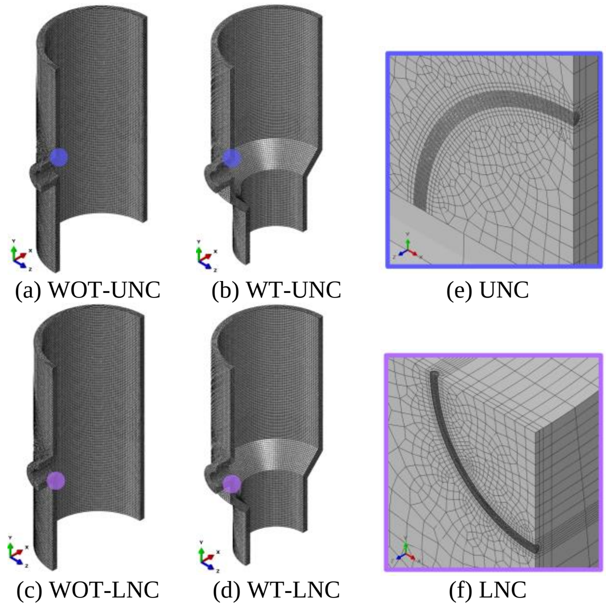


Fig. 1. FE models with nozzle corner crack

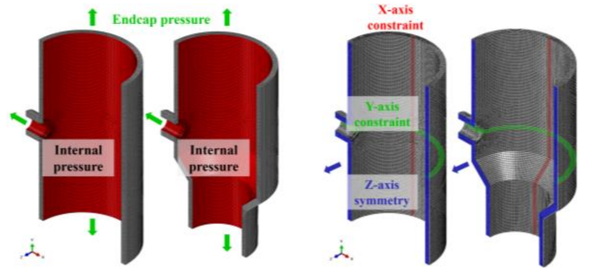
At the crack tip, 15-node wedge elements (C3D15) with quarter-point elements were used to simulate the stress singularity. In heat transfer analysis, 15-node wedge elements (D3C15) and 20-node brick elements (DC3D20) were used. The temperature-dependent material properties of SA-508 Gr. 3 Cl. 2 were taken from ASME BPVC Sec. II.

2.2 Loading and boundary conditions

As shown in Fig. 2(a), the internal pressure of 1 MPa was applied to the inner surfaces of the RV, nozzle and crack face to calculate K_{Ip}. Endcap pressure was applied to the end of the nozzle, upper face and lower face of the RV for both WT and WOT.

To calculate K_{It}, heat transfer analysis and thermal stress analysis were performed. The analysis was conducted considering cooldown (CD) condition, which induces tensile stress at the inner surface of the nozzle corner. Temperature transient of 321 ℃ to 22 ℃ was applied to the inner faces of the RV, nozzle and crack face at a rate of 55.6 ℃/hr.

During the entire analysis, the Z-axis symmetric boundary condition was applied except for the crack face, and boundary conditions to constrain movement in the X and Y-axis directions were considered as depicted in Fig. 2(b).



(a) Loading conditions (b) Boundary conditions

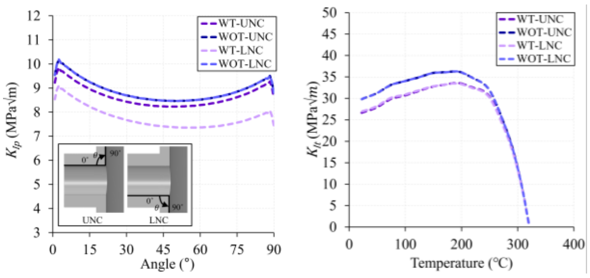
Fig. 2. Analysis conditions applied to FE models

3. Geometry effects of transition region

3.1 Stress intensity factors calculation

The K_{Ip} and K_{It} values were calculated for WOT and WT at UNC and LNC. Fig. 3(a) illustrated the distribution of K_{Ip} along the angle between the inner wall of the nozzle (0°) and the RV (90°). The distribution patterns of K_{Ip} were similar but the values of K_{Ip} were lower at WT than WOT. The maximum K_{Ip} decreased by 3.3% and 10.6% at UNC and LNC, respectively.

Fig. 3(b) presents the maximum values of K_{It} at the indicated temperature. The K_{It} values were lower at WT compared to WOT. The maximum values of K_{It} decreased by 7.4% and 7.7% at UNC and LNC, respectively. In the calculation of SIFs, the geometric effects were significant for LNC in both K_{Ip} and K_{It}. The difference in reduction of K_{It} between UNC and LNC showed 0.3%, whereas reduction of K_{Ip} showed a larger difference of approximately 7.3%.



(a) K_{Ip} distribution (b) Maximum K_{It} under CD condition

Fig. 3. SIF calculation results for nozzle corner cracks

3.2 P-T limit curve derivation

NPPs operate within the operational region on the P-T limit curve, which is derived from ASME BPVC Section XI, App. G. With the value of K_{Ic} calculated from Equation (1), the P-T limit curve was derived from Equation (2) based on the relationship among K_{Ic}, K_{Ip} and K_{It}.

$$K_{Ic} = 33.2 + 20.734\, exp[0.02(T - RT_{NDT})] \tag{1}$$

$$2K_{Ip} + K_{It} < K_{Ic} \tag{2}$$

where T is the temperature, and RT_{NDT} is the reference temperature for the nil-ductility transition. The value of RT_{NDT} is determined as 23.6 ℃ and 26.6 ℃ for the upper and the lower corner surfaces, respectively, considering an 80-year operational period with 95% capacity.

As shown in Fig. 4, based on P-T limit curve, the operational region of WT increased by 6.7% and 15.6% compared to WOT at UNC and LNC, respectively. The operational region increased higher at LNC, influenced by the transition region.

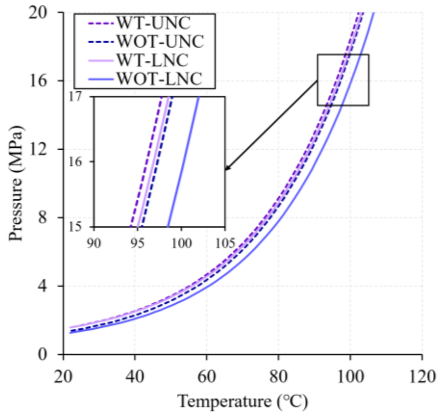


Fig. 4. RV nozzle P-T limit curves under CD transient

4. Conclusions

In this study, the geometric effects on nozzle crack analysis were evaluated by SIFs calculation and P-T limit curve derivation.

(1) SIFs due to pressure and thermal loading decreased regardless of crack location, when the transition region was present.
(2) The effect of transition region was more significant for K_{Ip} than K_{It} especially at LNC which is close to discontinuity.
(3) The P-T limit curve showed an increase of the operational region when the transition region was considered.

ACKNOWLEDGMENTS

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