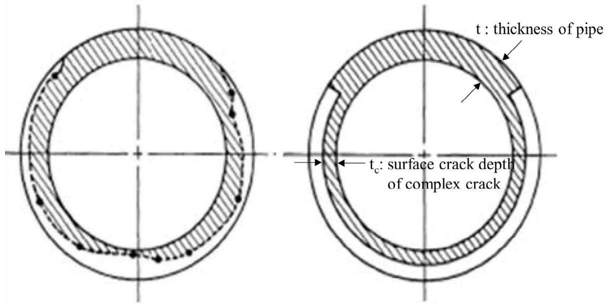
Finite element based crack opening displacement estimates for complex-cracked pipes under pure bending moment

Jae-Uk Jeong [a], Jae-Boong Choi [a], Do-Jun Shim [b], Yun-Jae Kim [c], Nam-Su Huh [d*]
[a] *School of Mechanical Engineering, Sungkyunkwan Univ., 2066 Seobu-ro, Jangan-gu, Suwon, Kyonggi-do*
[b] *Engineering Mechanics Corporation of Columbus, 3518 Riverside Drive- Suite 202, Columbus, OH 43221, U.S.A.*
[c] *Dept. of Mechanical Engineering, Korea Univ., 145 Anam-ro, Seongbuk-gu, Seoul*
[d] *Dept. of Mechanical System Design Engineering, Seoul National University of Science and Technology, 232 Gongneung-ro, Nowon-gu, Seoul*
[*] *Corresponding author: nam-su.huh@seoultech.ac.kr*

1. Introduction

A complex crack consists of a 360° circumferential surface crack at inner surface of pipe and a part through-wall crack in same plane of surface crack as shown in Fig. 1(a). Such cracks were firstly found at a recirculation-inlet-nozzle safe end of the Duane Arnold reactor in 1978 [1]. Also, several circumferential cracks were indicated at the dissimilar metal (DM) welds of pressurizer nozzle in the Wolf Creek nuclear power plant in 2006. Such circumferential indications could be developed into a complex-crack due to primary water stress corrosion crack (PWSCC) [2]. As researches of complex crack behavior, a series of complex-cracked pipe tests were carried out in the 1980's [3, 4]. From these researches, it has been revealed that a complex crack might be a severe flaw that can occur in service [5]. However, robust engineering estimation equations for predicting the behavior of complex shaped cracks have not been suggested. Instead, the method to calculate the J-integral and the COD using a reduced thickness analogy by simply adjusting the pipe radius and the thickness to account for the presence of the fully circumferential surface crack has been proposed. In this method, engineering estimation scheme for simple idealized through-wall crack is used [5]. However, it has been demonstrated that the predicted crack opening displacements (COD) by such scheme were not appropriate comparing with experimental data [6], which is due to the fact that such approach could not consider crack closure effect at the compressive stress region of complex crack plane. Kim et al. suggested the enhanced reference stress (ERS) method to predict the crack opening displacement (COD) and J-integral of complex cracked pipes considering the crack closure effect, and it presented the more accurate results compared to previous engineering estimation scheme [7]. However, this method has been only validated against limited experimental results. Thus, in the present paper, the ERS based COD estimates for complex cracked pipe is validated against detailed 3-dimensional finite element analyses considering crack closure effect due to inner surface crack existed in full circumference of pipe. In particular, the FE CODs of complex-cracked pipes are also compared with those of simple through-wall cracked pipes with reduced thickness.



(a) Typical complex crack (b) Simplified complex crack

Fig. 1. Geometries of complex cracks [4]

2. COD evaluation for complex cracked pipes

2.1 Geometry and FE Model

Fig. 1(b) depicts a simplified complex crack considered in this study. For the present work, a 6-inch nominal diameter (outer diameter: 6.625 inch [168.275 mm]) Schedule 120 (wall thickness: 0.57 inch [14.48 mm]) pipe was selected to compare with published pipe test data [8]. The TWC length and surface crack depth of complex crack were postulated 37% of pipe circumference and 31.6% of pipe thickness, respectively. The material is type 304 (TP304) stainless steel [8].

The general purpose FE program, ABAQUS, was used, and 20-nodes brick isoparametric elements

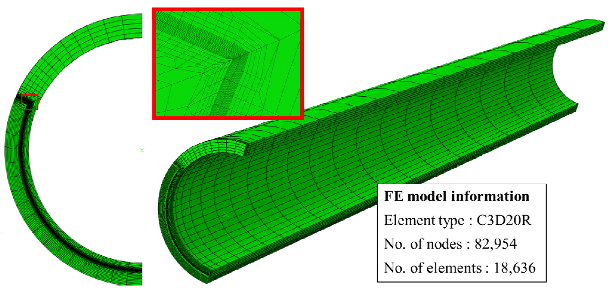


Fig. 2. Typical FE mesh of complex-cracked pipe employed in the present work

(C3D20R in ABAQUS element library) were employed. As for a loading condition, only pure bending was applied to the end of the pipe by applying rotational angle. Symmetry boundary conditions were applied so that only a quarter model was simulated. Contact option was used to consider the crack closure effect due to inner surface crack. The typical FE mesh for complex cracked pipe employed in the present study is shown in Fig. 2.

2.2 Results

The COD of complex-cracked pipes was evaluated based on FEA in this study. The FE CODs were obtained from mid-point of pipe thickness at crack center. Fig. 3 shows the comparison result of CODs according to bending moments. As shown in Fig. 3, the present FE CODs are in good agreement either with those based on ERS method or with test data. Thus, the confidence of the present FE analysis for complex cracked pipe is gained against experimental results.

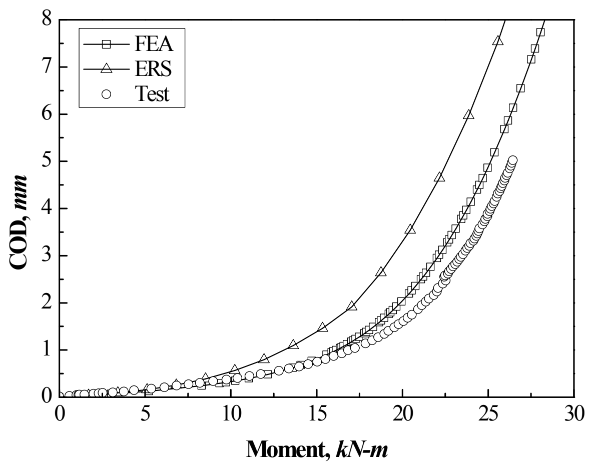


Fig. 3. Comparison of CODs from FE analysis with those from ERS and experiment.

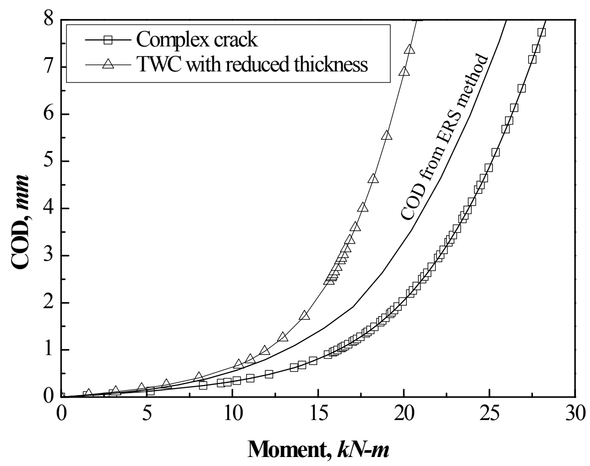


Fig. 4. Comparison of CODs from complex crack with those from simple through-wall crack with reduced thickness

Fig. 4 compares FE CODs of complex cracked pipe with those of simple through-wall cracked pipe with reduced thickness. As shown in Fig. 4, the values of COD from the pipe with reduced thickness are much higher than those from the pipe with complex crack, from which it can be concluded that the COD estimates of complex cracked pipe by using the simple through-wall crack with reduced thickness provide non-conservative COD or leak rate estimates for complex crack. In addition, although the results from ERS appear non-conservative COD than FE results, it provide more accurate than results from simple through-wall crack with reduced thickness.

3. Conclusions

In this study, the ERS based COD estimates for complex cracked pipes are validated against detailed 3-D FE analyses considering crack closure effect due to surface crack existed in full circumference of pipe. Firstly, the FE COD values agree well with experimental results. However, COD estimates of complex cracked pipe using the simple through-wall cracked pipe with reduced thickness provide non-conservative COD results. On the other hand, COD estimates based on the ERS method give more accurate results than the simple through-wall crack model using reduced thickness.

REFERENCES

[1] Pipe Crack Study Group, Investigation and Evaluation of Stress-Corrosion Cracking in Piping of Light Water Reactor plant, U.S. Nuclear Regulatory Commission, NUREG-0531, 1979.
[2] D. Rudland, D.-J. Shim, T. Zhang, and G. Wilkowski, Implication of Wolf Creek Indications - Final Report, Engineering Mechanics Corporation of Columbus, ML072470394, 2007.
[3] R.A. Hays, M.G. Vassilaros, and J.P. Gudas, Fracture Analysis of Welded Type 304 Stainless Steel Pipe Vol. 1, U.S. Nuclear Regulatory Commission, NUREG/CR-4538, 1986.
[4] G. Kramer, and V. Papaspyropoulos, An Assessment of Circumferentially Complex-Cracked Pipe Subjected to Bending, U.S. Nuclear Regulatory Commission, NUREG/CR-4687, 1986.
[5] G.M. Wilkowski, R.J. Olson, and P.M. Scott, State-of-the-Art Report on Piping Fracture Mechanics," U.S. Nuclear Regulatory Commission report, U.S. Nuclear Regulatory Commission, NUREG/CR-6540, BMI-2196, 1998
[6] S. Rahman, F.W. Brust, N. Ghadiali, and G. Wilkowski, Crack-Opening-Area Analyses for Circumferential Through-Wall Cracks in Pipes - Part II: Model Validations, International Journal of Pressure Vessels and Piping, Vol. 75, pp. 375-396, 1998.
[7] Y.J. Kim, N.S. Huh, and Y.J. Kim, Crack Opening Analysis of Complex Cracked Pipes, International Journal of Fracutre, Vol. 111, pp. 71-86, 2001.
[8] Pipe Fracture Encyclopedia, Volume 3:Pipe Fracture Test Data, Battelle, 1997.