

Reference Stress Based J and COD Estimations for LBB Analysis and Comparison with GE/EPRI Method

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ABSTRACT

Three-dimensional, elastic-plastic finite element (FE) analyses for circumferential through-wall cracked pipes are performed using actual tensile data of stainless steels, for two purposes. The first one is to validate the enhanced reference stress (ERS) method to estimate the J -integral and COD for circumferential through-wall cracked pipes, recently proposed by authors. The second one is to compare the J and COD results from the ERS method with those based on the GE/EPRI method, together with the FE results. It is found that the GE/EPRI method generally provides poor estimations of J and COD, and such poor estimation results from the error associated with the Ramberg-Osgood (R-O) fit. Moreover, the GE/EPRI results can be very sensitive to how the stress-strain data are fitted using the R-O relation. The most appropriate fitting range for the R-O fit depends on the material, and thus no specific guideline can be given. On the contrary, the J and COD estimations based on the ERS method give more accurate and robust results than the GE/EPRI estimation.

INTRODUCTION

Leak-before-Break (LBB) is an important concept for design and integrity evaluation of nuclear piping [1]. In general, application of the LBB procedure requires two steps. Firstly, the crack length corresponding to the detectable leakage rate should be calculated for a through-wall cracked pipe. For this step, engineering methods to estimate the crack opening displacement (COD) and leak rate are needed. The second step is to check whether this crack length is smaller than the limiting crack length that can cause unstable pipe fracture. For this second step, an engineering method to estimate the J -integral is needed. Currently, existing engineering J and COD estimation methods for the LBB analysis can be classified broadly into two categories: one using the Ramberg-Osgood fit to tensile data, and the other using actual tensile data. The first category includes, for instance, the GE/EPRI method [2,3]. One problem associated with this type of method is that the results are sensitive to how the stress-strain data are fitted using the Ramberg-Osgood relationship. The second category includes the reference stress approach [4], which is adopted in many defect assessment methods including R6 [5] due to its simplicity and robustness. Note that the current reference stress method recommends defining the reference stress using the plastic limit load [4,5], which is a convenient choice for practical application, but is a potential source of excessive conservatism. In this context, the enhanced reference stress method to estimate the J and COD was proposed in [6], for circumferential through-wall cracked pipes (this method will be referred to as the enhanced reference stress (ERS) method throughout this paper). Enhancement was made by re-defining the reference stress using the optimised reference load, instead of the plastic limit load, to improve the accuracy of J and COD estimations. Comparison of the proposed COD estimation equation with pipe test data was validated against 19 pipe test data, extracted from Kishida and Zahoor [7] and the Pipe Fracture Encyclopaedia [8], which showed overall excellent agreements.

In this paper, 3-D, elastic-plastic finite element (FE) analysis is performed using actual tensile data of stainless steels, used in Korean nuclear power plants, to gain more confidence of the proposed enhanced reference stress (ERS) method to estimate the J and COD. Moreover, these FE results are compared with those estimated according to the GE/EPRI method. Section 2 describes the FE analysis. Section 3 briefly describes the GE/EPRI method and the ERS method to estimate the J and COD. Comparisons of the FE J and COD results with these engineering estimations are given in Section 4 and the results are discussed in Section 5. Section 6 concludes the present work.

FINITE ELEMENT ANALYSIS

Material

For the present work, two different stress-strain data for two materials were considered: SA312 TP304 and SA312 TP316 stainless steels, which are typically used for Korean nuclear piping. For the SA312 TP304 stainless steel, experimental uni-axial stress-strain data at the temperature, $T=50^{\circ}\text{C}$, were taken. On the other hand, for the SA312 TP316 stainless steel, relevant data at $T=20^{\circ}\text{C}$ were taken. These stress-strain curves are shown in Fig. 1, and the relevant tensile data are summarised in Table 1.

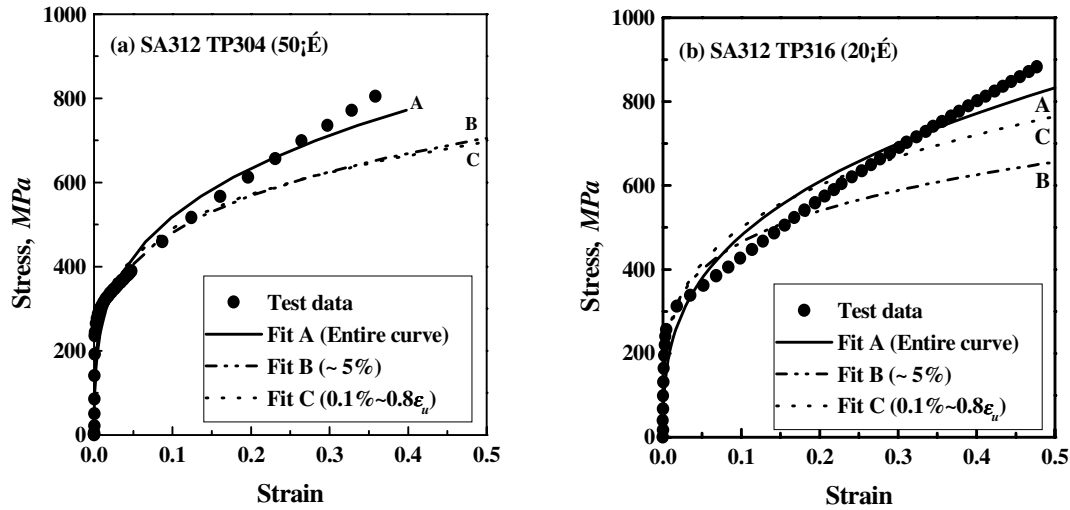


Fig. 1. Stress-strain curves and Ramberg-Osgood fitting results for (a) TP304 (50°C), and (b) TP316 (20°C).

Table 1: Summary of tensile data for TP304 and TP316, and the associated R-O parameters.

	E (GPa)	σ_y (MPa)	σ_u (MPa)	Fit A		Fit B		Fit C	
				α	n	α	n	α	n
TP304 (50°C)	204	269	559	7.33	3.52	5.97	4.30	4.22	4.72
TP316 (20°C)	206	234	545	10.23	2.96	3.39	4.72	4.77	3.82

Geometry

Figure 2 depicts a circumferential through-wall cracked pipe with relevant dimensions, considered in the present FE analysis. The outer radius and the thickness of the pipe are $R_o=177.8$ mm and $t=35.7$ mm, respectively, giving the value of the mean radius-to-thickness ratio, $R_m/t=4.48$. One crack length of $\theta/\pi=0.125$ was considered, which is regarded as an important values for typical LBB analyses. Two different loading conditions were considered, pure bending and axial tension.

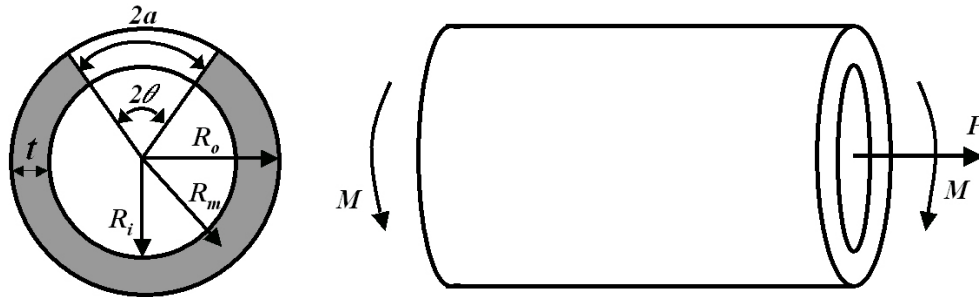


Fig. 2 Circumferential through-wall cracked pipes under axial tension and under pure bending.

Analysis

Using stress-strain data shown in Fig. 1, elastic-plastic analyses of the FE model of the circumferential through-wall cracked pipes (Fig. 2) were performed using ABAQUS [9]. For a given material, the experimental true stress-plastic strain data were directly given in the FE analysis. Materials were modelled as isotropic elastic-plastic materials that obey the incremental plasticity theory, and a small geometry change continuum FE model was employed. The number of elements and nodes in a typical FE mesh are 936 elements/5,561 nodes. Two elements were used through the thickness, which has been shown to provide the most reliable results for the COD calculation [10]. Considering the symmetric condition, only one quarter of the pipe was modelled. Figure 3 depicts the FE mesh for $\theta/\pi=0.125$. To avoid problems associated with incompressibility, reduced integration 20 node elements (element type C3D20R in ABAQUS) were used. The J -integral values were extracted from the FE results using a domain integral, as a function of the applied axial load or moment. The COD values, on the other hand, were determined from the FE displacement results in the mean thickness of the centre of the crack.

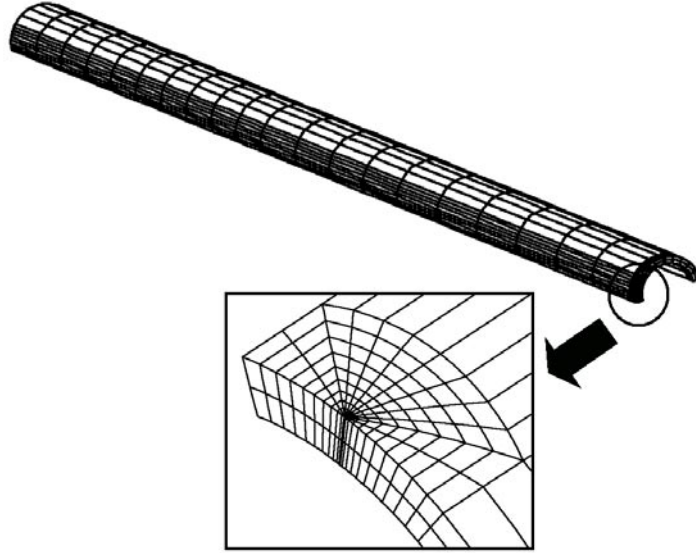


Fig. 3 A 3-D FE mesh for the circumferentially through-wall cracked pipe.

ENGINEERING J AND COD ESTIMATIONS

GE/EPRI Method

To apply the GE/EPRI estimation method, the material's tensile curve should be represented by the Ramberg-Osgood (R-O) relation:

$$\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha \left(\frac{\sigma}{\sigma_o} \right)^n \quad (1)$$

where σ_o is typically set to the yield stress of the material, σ_y , and $E\varepsilon_o = \sigma_o$, where E is the Young's modulus. Once the R-O parameters in eqn. (1), α and n , are found, then the J -integral and the COD (δ) for pipes with circumferential through-wall cracks (Fig. 2) under pure bending, for instance, can be estimated by [2].

$$J = \frac{K^2(a_e)}{E'} + \alpha \sigma_o \varepsilon_o R_m (\pi - \theta) \frac{\theta}{\pi} \cdot h_1 \cdot \left[\frac{M}{M_o} \right]^{n+1} ; \quad \delta = \frac{4Ma_e}{\pi R_m^2 E} \cdot V_1(a_e) + \alpha \varepsilon_o a \cdot h_2 \cdot \left[\frac{M}{M_o} \right]^n \quad (2)$$

In eqn. (2), K denotes the linear elastic stress intensity factor; M is a bending moment; and M_o is the normalising moment, for which the expression is given as:

$$M_o = 4\sigma_o R_m^2 t \left[\cos\left(\frac{\theta}{2}\right) - \frac{1}{2} \sin\theta \right] \quad (3)$$

The values of the dimensionless function V_1 and the plastic influence functions, h_1 and h_2 , calibrated from detailed FE analyses, can be found in [2]. The effective crack length a_e is defined as

$$a_e = a + \frac{1}{\beta\pi} \left(\frac{n-1}{n+1} \right) \left[\frac{K(a)}{\sigma_o} \right]^2 \left[1 + \left(\frac{M}{M_o} \right)^2 \right]^{-1} \quad (4)$$

where $\beta=2$ for plane stress and $\beta=6$ for plane strain. Since the plane stress condition dominates [10], $\beta=2$ is used in the present work.

As mentioned, application of the GE/EPRI method requires that the material's tensile data should be fitted using the R-O relation, eqn. (1). In the present work, three different ways for the R-O fit were performed, using the ROFIT program [11], developed by Battelle. The first way is to fit the entire true stress-strain data up to the ultimate tensile strength, referred to as the "fit A" in the present work. The second is to fit the data only up 5% strain [12], referred to as the "fit B". Finally, the third one is to fit the data from 0.1% strain to $0.8\varepsilon_{u,t}$, where $\varepsilon_{u,t}$ denotes the true ultimate strain,

referred to as the “fit C” [13]. The resulting R-O parameters, α and n , are listed in Table 1, and the resulting R-O fits are compared with experimental tensile data in Fig.1. It can be seen that the R-O parameters can be quite sensitive to the fitting interval for all cases.

Enhanced Reference Stress (ERS) Method

The J -integral can be estimated from

$$\frac{J}{J_e} = \frac{E\varepsilon_{ref}}{\sigma_{ref}} + \frac{1}{2} \frac{L_r^2 \sigma_{ref}}{E\varepsilon_{ref}} \quad \text{where} \quad L_r = \frac{\sigma_{ref}}{\sigma_y} = \frac{P}{P_o^*} = \frac{M}{M_o^*} \quad (5)$$

In eqn. (6), J_e denotes the elastically calculated value of J , and ε_{ref} is the true strain at the reference stress. The optimised reference load, P_o^* or M_o^* , is determined from

$$P_o^* = \gamma(\theta)P_o \quad ; \quad M_o^* = \gamma(\theta)M_o \quad ; \quad \gamma = 0.82 + 0.75\left(\frac{\theta}{\pi}\right) + 0.42\left(\frac{\theta}{\pi}\right)^2 \quad \text{for} \quad \theta/\pi \leq 0.5 \quad (6)$$

$$P_o = 2R_m t \sigma_y \left[\pi - \theta - 2 \sin^{-1} \left(\frac{1}{2} \sin \theta \right) \right] \quad ; \quad M_o = 4R_m^2 t \sigma_y \left[\cos \left(\frac{\theta}{2} \right) - \frac{\sin \theta}{2} \right]$$

The proposed J estimation is the same as the reference stress based J estimation in R6 [5], except for a slightly different definition of the reference stress, σ_{ref} . In R6, the reference stress is defined using the plastic limit load, P_o and M_o , but is defined here using the optimised reference load, P_o^* and M_o^* , to improve the accuracy of the J estimation.

For the COD (δ) estimation, the following equation is used:

$$\frac{\delta}{\delta_e} = \begin{cases} \frac{E\varepsilon_{ref}}{\sigma_{ref}} + \frac{1}{2} \frac{L_r^2 \sigma_{ref}}{E\varepsilon_{ref}} & \text{for} \quad 0 \leq L_r < 1 \\ \left(\frac{\delta}{\delta_e} \right)_{L_r=1} (L_r)^{n_1-1} & \text{for} \quad 1 \leq L_r \end{cases}, \quad (7)$$

In eqn. (7), $(\delta/\delta_e)_{L_r=1}$ denotes the value of (δ/δ_e) at $L_r=1$, calculated from the first equation in eqn. (7), so that eqn. (7) is continuous at $L_r=1$. The strain hardening index n_1 should be estimated from

$$n_1 = \frac{\ln[(\varepsilon_{u,t} - \sigma_{u,t}/E)/0.002]}{\ln[\sigma_{u,t}/\sigma_y]} \quad \text{where} \quad \sigma_{u,t} = (1 + \varepsilon_u)\sigma_u \quad \varepsilon_{u,t} = \ln(1 + \varepsilon_u) \quad (8)$$

Detailed descriptions on the derivation of eqns. (5)-(8) can be found from [6].

RESULTS

In Fig. 4, the FE results of the J -integral for the TP304 (50°C) are compared with corresponding engineering estimations according to two methods, the enhanced reference stress (ERS) method and the GE/EPRI method. The results are shown for two different loadings (axial tension and pure bending). Only one crack length is considered, $\theta/\pi=0.125$, which is regarded as an important value for typical LBB analyses. Note that for a conservative LBB analysis, the J -integral should be overestimated for a given load. Although the GE/EPRI J predictions are at least conservative for all cases, they are sensitive to the range of the R-O fit and their accuracy is generally poor. For this particular material, the Fit C provides the least conservative J estimation, whereas the Fit A gives the most conservative result. On the other hand, the ERS method provides a unique result. More importantly, it provides more accurate results than the GE/EPRI method for all cases. The results are still conservative, but are quite accurate up to a very high load. Figure 5 shows the corresponding results for the COD. For a conservative LBB analysis, the detectable leakage rate should be underestimated for a given load, which implies that the COD should be underestimated, in contrast to the J -integral. For the GE/EPRI method, the sensitivity to the range of the R-O fit is still observed, but for the COD estimation, the results are non-conservative for the LBB argument, compared to the FE results. Although the ERS method also gives non-conservative results, it gives more accurate results than the GE/EPRI method, compared to the FE results.

In Figs. 6 and 7, the FE results of the J -integral and the COD for the TP316 (20°C) are compared with corresponding engineering estimations. In general, the tendency is similar to that for the TP304 material. The difference is that the GE/EPRI results for this case are more sensitive to the R-O fitting range than those for the TP304 material. Such difference may result from the fact that, for the TP316 case, none of three R-O fits is close to the experimental stress-strain data even at a small strain range (see Fig. 1). Another difference is that, for this case, the Fit B gives the best result, whereas for the TP304 case, Fit C does (see Fig. 4). Thus the most appropriate fitting range for the R-O fit depends on the material, and thus no specific guideline can be given. On the contrary, the ERS method again provides overall more accurate results for not only the J -integral but also the COD, than the GE/EPRI method.

In general, the ERS method provides a robust estimation of the J and COD, since it does not require the R-O fit of the stress-strain data, and directly uses the stress-strain data of the material. In contrast, the GE/EPRI results require the R-O fit, and can strongly depend on the fitting range for the R-O fit.

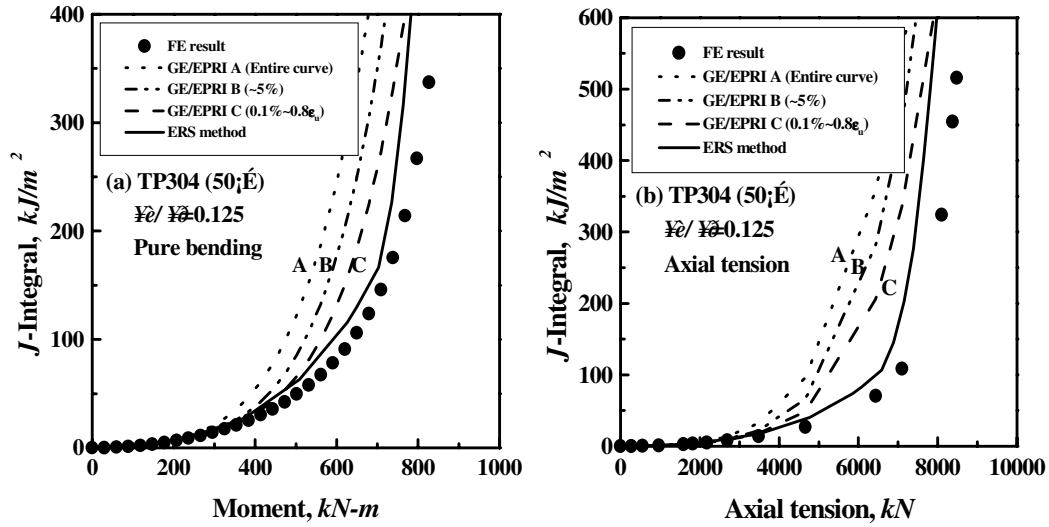


Fig. 4. Comparison of FE J values with those estimated from engineering estimation methods, the GE/EPRI method (three fits) and the enhanced reference stress (ERS) method, for SA312 TP304 (50□): under pure bending and under axial tension.

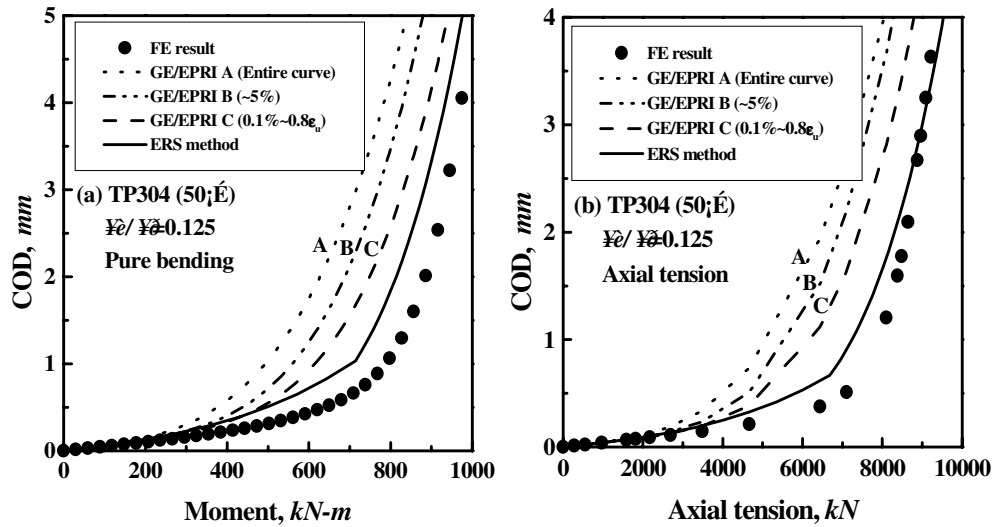


Fig. 5 Comparison of FE COD values with those estimated from engineering estimation methods, the GE/EPRI method (three fits) and the enhanced reference stress (ERS) method, for SA312 TP304 (50□): under pure bending and under axial tension.

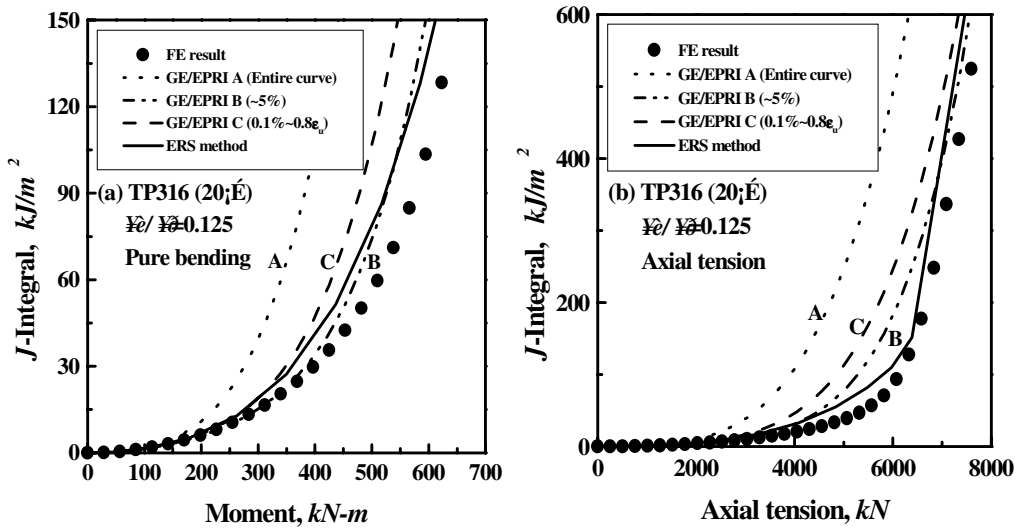


Fig. 6. Comparison of FE J values with those estimated from engineering estimation methods, the GE/EPRI method (three fits) and the enhanced reference stress (ERS) method, for SA312 TP316 (20°C): under pure bending and under axial tension.

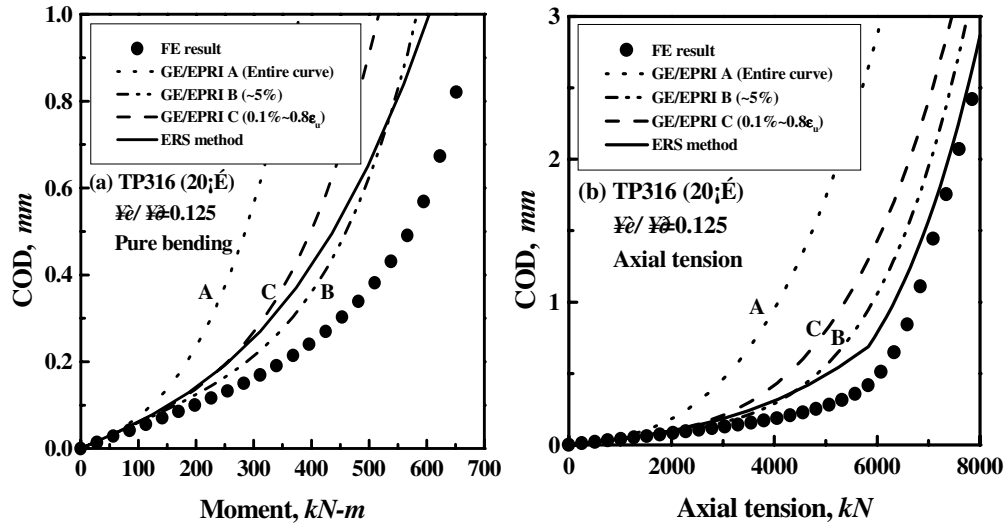


Fig. 7. Comparison of FE COD values with those estimated from engineering estimation methods, the GE/EPRI method (three fits) and the enhanced reference stress (ERS) method, for SA312 TP316 (20°C): under pure bending and under axial tension.

DISCUSSION

The results in the previous section firstly confirm the well-known fact for many years that the J and COD estimations according to the GE/EPRI method can be very sensitive to how the stress-strain data are fitted using the R-O relation. Moreover, no tendency can be found regarding the most appropriate fitting range for the R-O fit. For example, for the TP304 (50°C) case, the Fit C provides the most accurate J and COD estimations (Figs. 4 and 5) among the three fits. On the other hand, for the TP316 (20°C) case, the Fit B gives the most accurate J and COD estimations (Figs. 6 and 7). Most importantly, the GE/EPRI method provides overall poor estimations for the J -integral and the COD. A natural question is whether such poor estimations result from inherent errors in the GE/EPRI method or from the R-O fit. To resolve this issue, the following FE analysis has been performed. In the FE analysis, deformation plasticity option was invoked within ABAQUS, and the R-O parameters corresponding to the Fit A (entire curve fit) for the TP304 (50°C) material ($\alpha=7.33$ and $n=3.52$; see Table 2) were given. The resulting R-O fit is compared well with the stress-strain data, as shown in Fig. 1a. Figure 8 compares the values of the FE J -integral and the COD, resulting from the deformation plasticity option, with those

estimated according to the GE/EPRI method and with the FE results using actual stress-strain data (based on incremental plasticity theory). The results firstly show that the FE results based on the deformation plasticity are very close to the GE/EPRI estimations for both J and COD. However, they differ significantly from the FE results using actual stress-strain data (based on incremental plasticity theory). Noting that for the same stress-strain data input, the calculation option (either deformation plasticity or incremental plasticity option) has a minimal effect on J and COD, it can be concluded that the poor estimation of the GE/EPRI method is mainly due to the R-O fit to the stress-strain data. Although the results in the present work are limited for three stainless steels, authors have also done other cases involving more materials including materials with Lüders strain, to investigate the accuracy of the GE/EPRI predictions. For all cases considered by the authors, the GE/EPRI method consistently provides conservative J estimation but non-conservative COD estimation (for the LBB analysis, see Section 4), compared to the FE J and COD results. Such non-conservatism in the GE/EPRI COD estimation is consistent with other findings in the literature [7,14].

The proposed J and COD estimation equations based on the proposed enhanced reference stress (ERS) approach give robust results, since it does not involve any fitting of the tensile data. Moreover, the ERS method gives overall more accurate results than the GE/EPRI estimation. The J estimations are quite accurate compared to the FE results, but still conservative for defect assessment. The COD estimation results, however, are slightly non-conservative, although they are still closer to the FE results, compared to the GE/EPRI results. On the contrary, comparison with a large set of published pipe test data in [6] showed that the estimated COD values were in excellent agreement. The present results, together with experimental validation in [6], provide sufficient confidence in the use of the proposed enhanced reference stress method to the LBB analysis. It has been shown that, compared to the GE/EPRI method, the proposed method is not only accurate but also simple to apply. The application of the enhanced reference stress method to other problems, such as a circumferential through-wall cracked pipe with a weldment and a pipe operating at high temperatures (creep regime), is currently being undertaken, and the results will be reported later.

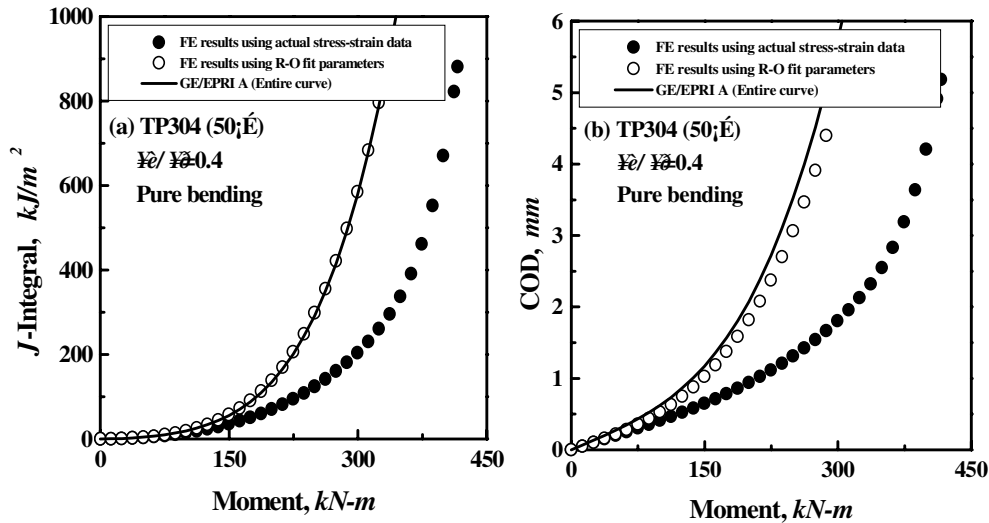


Fig. 8. Comparison of FE J and COD values using the R-O fit parameters for the Fit A to the TP304 tensile data, with the GE/EPRI predictions and the FE results using actual stress-strain data.

CONCLUSIONS

In this paper, three dimensional, elastic-plastic finite element analyses for circumferential through-wall cracked pipes are performed using actual tensile data of stainless steels, for two purposes. The first one is to validate the recently-proposed enhanced reference stress (ERS) method to estimate the J -integral and COD for circumferential through-wall cracked pipes [6]. The second one is to compare the J and COD results from the ERS method with those based on the GE/EPRI method, together with the FE results. The following conclusions can be drawn from the present analysis:

- The J and COD estimations according to the GE/EPRI method are generally inaccurate, and such inaccuracy results from the Ramberg-Osgood (R-O) fit. Moreover, the GE/EPRI prediction for the J and COD can be very sensitive to how the stress-strain data are fitted using the R-O relation. The most appropriate fitting range for the R-O fit depends on the material, and thus no specific guideline can be given.
- The J and COD estimations based on the proposed ERS method give more robust and more accurate results than the GE/EPRI estimation. The present results, together with the experimental validation presented in the previous paper [6], provide sufficient confidence in using the proposed method in the LBB analysis.

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