Engineering J Estimation Methods for Leak-Before-Break Analyses of Nuclear Piping*

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The present work presents a method to estimate elastic-plastic J for circumferential through-wall cracked pipes for the Leak-Before-Break (LBB) analysis of pressurized piping. The proposed method is based on the GE/EPRI approach and the key issue is to propose a robust Ramberg-Osgood fitting procedure. Two different estimation schemes are given, one for the case when full stress-strain data are available, and the other for the case when only yield and ultimate tensile strengths are available. The proposed J estimates are compared with those from extensive elastic-plastic finite element (FE) analyses. Experimental validation is also performed by comparing maximum moments predicted by fracture mechanics analysis using the proposed J estimates with those from full-scale pipe test. Both results show sufficient confidence in the accuracy of the proposed J estimates.

Key Words: Circumferential Through-Wall Cracked Pipe, J -Integral, GE/EPRI Approach, Leak-Before-Break Analysis

1. Introduction

Reliable estimates of the elastic-plastic J -integral and crack opening displacement (COD) for circumferential through-wall cracked pipes are essential to the Leak-Before-Break (LBB) analysis^{(1)–(10)} of nuclear piping. In Part I⁽¹¹⁾, the authors have proposed methods to estimate elastic-plastic COD for circumferential through-wall cracked pipes. Proposed methods were based not only on the GE/EPRI approach^{(12),(13)} but also on the reference stress approach^{(8),(14),(15)}. For each approach, two different estimation schemes have been given, one for the case when full stress-strain data are available, and the other for the case when only yield and ultimate tensile strengths are available. In particular, for the GE/EPRI approach, the key point was to propose a robust Ramberg-Osgood (R-O) fitting procedure, i.e., robust determination of the R-O parameters. Investigation of relevance of the R-O fit to elastic-plastic COD estimates has led to a robust way of determining the R-O parameters, not only for the case when detailed information on full stress-strain data are

available but also for the case when only yield and ultimate tensile strengths are available. The COD estimates according to the GE/EPRI approach, using the R-O parameters determined from the proposed R-O fitting procedures, overall compared well with the published pipe test data. For the reference stress approach, the method to estimate COD, for the case when full stress-strain data are available, has been proposed by one of the authors⁽⁸⁾. Thus the key issue was to propose a method for the case when only yield and ultimate tensile strengths are available. The COD estimates according to the method based on full stress-strain data were in excellent agreement with pipe test data. Moreover, the method based on limited tensile properties gave similar COD estimates to that based on full stress-strain data for all test data. Although the COD estimation shares some common aspects to the J estimates, the results in Part I cannot be directly applied, particularly for the case for limited tensile properties. This is because, for the conservative LBB analysis, the COD (or leak rate) should be underestimated for a given load, whereas the J -integral should be overestimated.

The present work presents a reliable method to estimate elastic-plastic J for circumferential through-wall cracked pipes. As in Part I, both the GE/EPRI method and the reference stress method could be presented. For the reference stress method, however, the authors have already published relevant results (see for instance Refs. (7)–(10)). Moreover for the case when only yield and tensile

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strengths are available, the J estimation method is already available, which is referred to as the Option 1 in R6⁽¹⁵⁾. Thus this work concentrates only on the J estimate based on the GE/EPRI method, and thus the key point is to propose a robust R-O fitting procedure for J estimates. A particular emphasis is made on a R-O fit for the case when only yield and tensile strengths are available.

2. J Estimates Based on GE/EPRI Approach

2.1 GE/EPRI J estimates

The GE/EPRI estimation procedure^{(12),(13)}, which has been developed on the basis of elastic-plastic finite element (FE) results, interpolates over the entire range of elastic-plastic deformation from small scale yielding to fully plastic conditions including contained plasticity. The limiting cases of elastic and fully plastic solutions are utilized appropriately to arrive at the elastic-plastic estimates. Consider for instance a through-wall cracked pipe under global bending M (Fig. 1). The geometry of the pipe is characterized by its mean radius R_m , and the thickness t ; the crack by its length a or its angle θ ($= a/R_m$). Application of the GE/EPRI approach to estimate the elastic-plastic J for such through-wall cracked pipe is briefly summarized below.

Assume that a material behavior is governed by the R-O stress-strain law,

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

where σ_o is a normalizing stress, typically taken to be the 0.2% proof stress, $\sigma_o = \sigma_{0.2}$; $E\varepsilon_o = \sigma_o$ with E Young's modulus; and α and n are constants (will be termed as the R-O parameters). The elastic-plastic J can then be estimated from

$$J = J_e(a_e) + J_p \quad (2)$$

In Eq. (2), J_e denotes the elastically calculated value of J ,

$$J_e(a_e) = \frac{K(a_e)^2}{E'} \quad (3)$$

In Eq. (3), K denotes the linear elastic stress intensity factor; $E' = E$ for plane stress and $E' = E/(1 - \nu^2)$ for plane strain where ν denotes Poisson's ratio. The effective half-crack length adjusted to include Irwin's small-scale yielding correction, a_e , is given by

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

Fig. 1 Schematic illustration of a circumferential through-wall cracked pipe under bending

where $\beta = 2$ for plane stress and $\beta = 6$ for plane strain. In Eq. (4), the normalizing moment M_o is typically taken to be the plastic limit moment of cracked component for the material having the limiting stress of σ_o

$$M_o = 4\sigma_o R_m^2 t \left[\cos\left(\frac{\theta}{2}\right) - \frac{1}{2} \sin\theta \right] \quad (5)$$

The plastic component of J , J_p , on the other hand, is given by

$$J_p = \alpha \sigma_o \varepsilon_o R_m \theta \left(1 - \frac{\theta}{\pi} \right) h_1 \left[\frac{M}{M_o} \right]^{n+1} \quad (6)$$

where the values of the plastic influence function, h_1 , as a function of R_m/t , θ/π and n , are typically calibrated from detailed FE analyses, for instance, see Refs. (5), (12) and (13).

2.2 Relevant R-O fit to accurate J estimates

One important point in the above GE/EPRI approach is that the estimated J depends on the R-O parameters, α and n , see for instance Eqs. (1)–(6). It should be noted that there could be a number of different ways to fit stress-strain data using the R-O relationship, which in turn could provide very different J estimates. A natural question would be how tensile data should be fitted according to Eq. (1) to provide best J estimates.

To investigate the effect of the R-O idealization of tensile data on estimated J based on the GE/EPRI approach, elastic-plastic analyses of the FE model of the circumferential through-wall cracked pipes under global bending (Fig. 1) are performed using ABAQUS⁽¹⁶⁾. For illustrative purpose, the pipe geometry of $R_m/t = 10$ is considered, which is a typical value for nuclear piping. Regarding crack length, two different values of θ/π are considered, $\theta/\pi = 0.125$ and 0.4 , reflecting short and long cracks. Considering the symmetric condition, only one quarter of the pipe is modeled. Figure 2 depicts the FE mesh for $\theta/\pi = 0.125$, where the number of elements and nodes in the FE mesh are 936 elements/5561 nodes. The crack tip is designed with focused elements, and in the crack tip region, a ring of 12 wedge-shaped elements

Fig. 2 A 3-D FE mesh for the circumferential through-wall cracked pipe

were used. Through the pipe thickness, two elements are used. To avoid problems associated with incompressibility, the reduced integration 20 node element (element type C3D20R in ABAQUS) is used.

In the present work, two types of FE analyses are performed. The first type is based on incremental plasticity using actual stress-strain data. For this purpose, Type 316 stainless steel at the room temperature is selected, exhibiting continuously hardening behavior. True stress-strain data for this material are shown in Fig. 3, and relevant properties are summarized in Table 1. For the FE analysis, actual true stress-strain data, shown in Fig. 3, are directly given in the FE analysis. Material is modeled as isotropic elastic-plastic materials that obey J_2 flow theory, and a small geometry change continuum FE model is employed. The resulting FE J value can be regarded as the “reference” value for comparison. The second type of the FE analysis is based on deformation plasticity using the R-O material, see Eq. (1). In this case, the true stress-strain data for the Type 316 stainless steel, shown in Fig. 3, are fitted using the R-O relationship. For this purpose, three different ways of the R-O fit are employed. 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 true stress-strain data

Fig. 3 Normalized true stress-strain data for five materials considered in the present work

Table 1 Summary of tensile properties used in the present FE analysis, and relevant R-O parameters

	E (GPa)	$\sigma_{0.2}$ (MPa)	σ_u (MPa)	Conventional method						Proposed method			
				Fit A		Fit B		Fit C		Fit (full)		Fit (limited)	
				α	n	α	n	α	n	α	n	α	n
SA312 TP316 (20°C)	206	234.5	547.7	10.23	2.96	3.39	4.72	4.77	3.82	1.76	6.74	1.76	7.41
SA312 TP316 (296°C)	190	165.5	460.7	8.42	2.92	5.76	4.11	6.26	3.46	2.30	4.86	2.30	6.44
SA312 TP304 (50°C)	204	268.9	562.5	7.33	3.52	5.97	4.30	4.22	4.72	1.52	7.27	1.52	8.22
Carbon Steel (20°C)	206	285.4	417.5	7.37	5.21	5.58	7.56	7.02	5.40	1.44	12.66	1.44	13.23
Medium Ferritic Steel (20°C)	206	542.4	706.3	2.98	7.39	2.09	12.25	2.83	7.82	0.76	16.08	0.76	17.32

only up to 5% strain⁽¹⁷⁾, referred to as the “fit B”. The third one is to fit the true stress-strain 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”⁽¹⁸⁾. It should be noted that all above three fits are based on true stress-strain data, but the difference is the fitting range. The resulting R-O fits are compared with true stress-strain data in Fig. 4 (a), and associated R-O parameters are tabulated in Table 1. For the FE analysis based on deformation plasticity, the R-O parameters in Table 1 are used with the deformation option within ABAQUS. For both types of FE analyses, the J -integral values are extracted from the FE results using a domain integral within ABAQUS. For the 3-D crack front, J values vary along the crack front, and in the present work, the average value of J along the crack front is reported.

Figure 4 (c) and (d) compare FE J values based on incremental plasticity with those based on deformation plasticity. As mentioned, the FE J results based on incremental plasticity are taken as the reference for comparison. The FE results based on deformation plasticity using the R-O parameters resulting from three fits with different fitting ranges (Fits A, B and C) are then compared. As expected, different sets of the R-O parameters, resulting from different R-O fits, give different J estimates. Noting that for a conservative fracture mechanics analysis, the J -integral should be overestimated for a given load, and thus the J estimates based on deformation plasticity are at least conservative. However, accuracy depends on the fitting range. For instance, the Fit B gives the least conservative J estimates for the present case, but the Fit A the most conservative ones. It gives a contrast to the fact that the Fit A agrees best with true stress-strain data, but the Fit B is the worst fit.

At this point, one interesting point is worth noting. Figure 4 (b) shows the same result as Fig. 4 (a), but in a different scale (in the small strain range up to 5% strain). Resemblance between Fig. 4 (b) and Fig. 4 (c) and (d) is remarkable. This provides a hint to the most appropriate R-O fit for J estimates that the tensile data should be fitted as accurately as possible in a small strain range. Such observation is consistent to a general recommendation of the R-O fit to the true stress-strain data only up to 5% strain. Thus, in principle, one could find the most appropriate R-O fit by comparing tensile data with the fit in a small strain range, say, up to 5%. On the other hand, such practice also has a limitation in the sense that it requires detailed stress-strain data that are often not available. In this respect, a robust R-O fitting method is highly desired.

2.3 Proposed R-O fit for the GE/EPRI approach — When full stress-strain data available

In the previous section, it has been argued that deviation of the R-O fit to actual stress-strain data in a small strain range might be a source of inaccuracy in the estimated J . In this respect, the stress-strain data in a small

Fig. 4 (a) and (b) Stress-strain data in different strain ranges with its R-O fits for the Type 316 stainless; (c) and (d) comparison of FE J values based on incremental plasticity using actual stress-strain data with those based on deformation plasticity using three different R-O fits. Descriptions on the R-O fit and associated R-O parameters can be found in Table 1.

strain range should be fitted as accurately as possible. One notable point is that existing R-O fitting methods tend to use true stress-strain data. Seemingly reasonable, the use of true stress-strain data has an inherent problem for the following reason. The strain hardening rate for typical materials tends to be lower at a small strain range and then becomes higher at a large strain range. Thus the use of true stress-strain data for the R-O fit tends to overestimate actual strain hardening at a small strain range, as shown in Fig. 4. This suggests another alternative to use the engineering stress-strain data for fit, instead of true stress-strain data. In fact, it can be seen from Fig. 4 that the Fit B, giving the best J estimates, is indeed closest to engineering stress-strain data.

Based on the above argument, a robust scheme for the R-O fit can be proposed as follows. Firstly the parameter α in the R-O relation, Eq. (1), can be determined so that the 0.2% proof stress, $\sigma_{0.2}$, has a consistent definition:

$$\alpha = \frac{0.002E}{\sigma_{0.2}} \quad (7)$$

Then the parameter n is easily determined from

$$n = \frac{\ln \left[\frac{(E\varepsilon_u - \sigma_u)}{0.002E} \right]}{\ln(\sigma_u/\sigma_{0.2})} \quad (8)$$

where σ_u and ε_u denote the ultimate tensile strength and ultimate tensile strain, respectively. It should be noted that the proposed R-O fit is robust in the sense that for a given material, a unique set of the R-O parameters can be determined. The resulting R-O parameters for the Type 316 stainless steel are tabulated in Table 1 (denoted as “Fit (full)”), and approximated stress-strain curve is compared with actual stress-strain data in Fig. 5 (a) and (b). Comparison of the results in Fig. 5 with those in Fig. 4 shows that the proposed method indeed provides more accurate fits in a small strain range. Elastic-plastic J values from FE analysis based on deformation plasticity using the proposed R-O fit are compared with those from FE analysis based on incremental plasticity using actual stress-strain data in Fig. 5 (c) and (d). Comparison of the results in Fig. 5 with those in Fig. 4 shows that the proposed R-O fit provides J values closer to those based on incremental plasticity, compared to existing R-O fits, implying that the proposed R-O fit indeed provides better J estimates.

2.4 Proposed R-O fit for the GE/EPRI approach — When only yield and ultimate tensile strength data available

The proposed R-O fit, Eqs. (7) and (8), can be used when the ultimate tensile strain ε_u is available (or full

Fig. 5 (a) and (b) Stress-strain data in different strain ranges with the proposed R-O fits for the Type 316 stainless; (c) and (d) comparison of FE J values based on incremental plasticity using actual stress-strain data with those based on deformation plasticity using the proposed R-O fits

stress-strain data are available). In practice, however, information on ε_u (or full stress-strain data) is often quite limited, and only limited information on tensile properties may be available such as the yield and ultimate tensile strengths, $\sigma_{0.2}$ and σ_u . Note that Eq. (7) suggests that the parameter α can be easily determined when the 0.2% proof (yield) strength is available, and thus the problem remains how to estimate n . At this point, it is worth mentioning that for accurate J estimates, the value of n should be based on engineering stress-strain data, instead of true stress-strain data. Figure 6 shows $1/n$ values, determined from the power law fit to engineering stress-strain data for various materials⁽¹⁹⁾. Based on these data, the following equation is proposed to estimate n from $\sigma_{0.2}/\sigma_u$:

$$\frac{1}{n} = 0.324 - 0.666 \left(\frac{\sigma_{0.2}}{\sigma_u} \right) + 0.660 \left(\frac{\sigma_{0.2}}{\sigma_u} \right)^2 - 0.318 \left(\frac{\sigma_{0.2}}{\sigma_u} \right)^3 \quad (9)$$

which is shown in Fig. 6. It can be seen that Eq. (9) provides a lower bound to $1/n$ (upper bound to n) of engineering stress-strain data. It is worth comparing with the following equation relating the ratio, $\sigma_u/\sigma_{0.2}$, of ultimate to yield strength to n , recommended in Ref. (20):

$$\frac{\sigma_u}{\sigma_{0.2}} = \left(\frac{1}{0.002n} \right)^{1/n} \exp \left(-\frac{1}{n} \right) \quad (10)$$

which is also shown in Fig. 6. It can be seen that Eq. (10)

Fig. 6 Relations of $\sigma_{0.2}/\sigma_u$ and n from engineering stress-strain data for various hardening materials

provides an upper bound to $1/n$ (lower bound to n) of engineering stress-strain data for continuously hardening materials and a mean to $1/n$ of those for materials with Lüders strain.

Thus when only yield and tensile strengths are available, the R-O parameters, α and n , should be determined from Eqs. (7) and (9), respectively^{*1}. Approximated stress-strain curve according to the proposed R-O fit is compared with actual stress-strain data in Fig. 5, with associated R-O parameters listed in Table 1 (denoted as "Fit (limited)"). Comparison of the results in Fig. 5 with those in Fig. 4 shows that the proposed method in fact pro-

vides accurate fits in small strain ranges. Elastic-plastic J values from FE analysis based on deformation plasticity using the proposed R-O fit are also compared with those from FE analysis based on incremental plasticity using actual stress-strain data in Fig. 5, showing that the proposed R-O fit provides better J estimates, compared to existing R-O fits.

3. Finite Element Validation

3.1 Materials and FE analyses

To gain confidence in the proposed R-O fit for the GE/EPRI approach to estimate elastic-plastic J , more systematic comparison using different materials is performed. A total of five materials are considered: (i) Type 304 stainless steel at 50°C, (ii) Type 316 at 20°C, (iii) Type 316 at 296°C, (iv) the carbon steel at 20°C and (v) the medium ferritic steel at 20°C. The first three materials show continuous hardening behavior, whereas the last two materials exhibit discontinuous hardening behavior. The relevant elastic and plastic properties for these materials are listed in Table 1, and true stress-strain data are shown in Fig. 3. It can be seen that these materials show quite different strain hardening capacities and thus yield-to-tensile strength ratios. Values of the R-O parameters, α and n , resulting from five different ways of R-O fits (including the proposed two ways of fits), are also tabulated in Table 1. For systematic analyses, two value of R_m/t are considered, $R_m/t = 5$ and 10; and three different value of θ/π , $\theta/\pi = 0.125$, 0.25 and 0.4. For loading condition, only global bending was considered. Noting that the purpose of the present work is to investigate the accuracy of the proposed R-O fit for elastic-plastic J estimates, the J values are determined directly from elastic-plastic FE analysis based on deformation plasticity using the Ramberg-Osgood parameters. This also reduces possible errors associated with interpolation and extrapolation in using values of the plastic influence function, given in Ref. (12) for instance.

3.2 Results

Comparison of FE J values based on incremental plasticity with those based on deformation plasticity using the proposed R-O fits shows overall good agreements for extensive cases considered in the present work. For the sake of space, only selected results are shown in Figs. 7–10. It shows that the J estimates based on the proposed R-O fits agree very well with FE J values up to sufficiently high loads, even for the fit with only yield and ultimate

tensile strengths. The results shown in Figs. 7–10 provide sufficient confidence in the use of the proposed R-O fits to estimate elastic-plastic J for circumferential through-wall cracked pipes based on the GE/EPRI method.

4. Experimental Validation

4.1 Summary of pipe test data

To gain further confidence, experimental validation is performed, where maximum moments of the circumferential through-wall cracked pipes under bending, predicted based on fracture mechanics analysis using the proposed J estimates, are compared with experimentally-measured ones from published full-scale pipe test data. Published pipe test data were taken from the Pipe Fracture Encyclopedia⁽²¹⁾ and Kishida and Zahoor⁽²²⁾. These data are classified broadly into three categories, as summarized below.

The first one is for base metal test data resulting from testing pipes made of homogeneous materials under quasi-static monotonic loading. A total of ten test data were considered, of which brief information is given in Table 2. Tests covered a wide range of R_m/t from $R_m/t = 5.22$ to 15.16, and of θ/π from $\theta/\pi = 0.0625$ to 0.39, although most tests were biased to deep cracks. In terms of materials, two classes of materials were employed, carbon steels (exhibiting possibly discontinuous hardening behavior) and austenitic stainless steels (showing continuous hardening behavior). The second set is for weld metal test data under quasi-static monotonic bending, and a total of five test data were considered. For all tests, the pre-crack was placed in the center of the weld metal. Similarly to the base metal test data, the values of R_m/t ranges from $R_m/t = \sim 5$ to ~ 11 , and of θ/π from $\theta/\pi = 0.0625$ to 0.37. The final data set is for base metal test data under quasi-static cyclic bending. A total of five test data were considered. Values of R_m/t are around 5, and those of θ/π around 0.37. Detailed information on full-scale pipe tests can be found in Refs. (21) and (22), together with relevant full stress-strain data and fracture toughness data (in terms of the $J-R$ curve) for elastic-plastic fracture mechanics analysis.

4.2 Fracture mechanics analysis and results

Maximum moments of the circumferential through-wall cracked pipe under global bending are predicted based on elastic-plastic fracture mechanics method. The failure assessment diagram (FAD) approach is employed. Firstly for a given pipe and crack geometries, variations of elastic-plastic J with the applied bending moment are estimated according to the GE/EPRI approach using the proposed R-O fitting parameters, from which the FAD can be constructed⁽²³⁾. This method is referred to as the Option 3 in R6⁽¹⁵⁾. Then using the $J-R$ curve of the material of interest, the tearing locus can be constructed. Figure 11 schematically illustrates how to estimate maximum (instability) moment ($M_{\max}$) based on the FAD approach, on

*1 It could be noted that data shown in Fig. 6 are taken from more than hundred metals and alloys, having a wide range of yield-to-tensile strength ratios. These data were obtained in the course of the European BriteEuram project, SINTAP (Structural Integrity Assessment Procedure for European Industry). As they cover most structural steels, Eq. (9) is believed to be general, that is, could be applied to any structural steel.

Fig. 7 Comparison of FE J values based on incremental plasticity using actual stress-strain data with those based on deformation plasticity using the proposed R-O fits, for the type 304 stainless steel at 50°C

Fig. 8 Comparison of FE J values based on incremental plasticity using actual stress-strain data with those based on deformation plasticity using the proposed R-O fits, for the type 316 stainless steel at 20°C

Fig. 9 Comparison of FE J values based on incremental plasticity using actual stress-strain data with those based on deformation plasticity using the proposed R-O fits, for the carbon steel at 20°C

which more detailed information can be found in R6⁽¹⁵⁾. Experimental maximum moments are compared with predicted ones according to the proposed method in Table 3. Noting that the results are given in terms of the ratio of the predicted maximum moment to experimental one, the ratio being less than unity implies that the predicted moment

is smaller than experimental one and thus is conservative. Two points are worth noting. Firstly, the results in Table 3 show that the ratio for the proposed method is greater than unity only for the case of 1.1.1.26 where the prediction is non-conservative by 5 to 10%. For all other cases, however, the ratios are less than unity, ranging from 0.62 to

Fig. 10 Comparison of FE J values based on incremental plasticity using actual stress-strain data with those based on deformation plasticity using the proposed R-O fits, for the medium ferritic steel at 20°C

Fig. 11 Schematic illustration for determination of maximum moment based on the failure assessment diagram approach

1.00, and thus the predictions are conservative. The second point is that predictions based on limited tensile data give close (but overall slightly conservative) results, compared to those based on full stress-strain data. Together with the results that the J estimates based on limited tensile data are close to those based on full stress-strain data in section 3, such results provide sufficient confidence in the proposed R-O fit using only yield and tensile strengths.

For comparison, the maximum moments are also predicted using the J estimates based on the R6 Option 2 method⁽¹⁵⁾ based on full stress-strain data. Furthermore, for selected cases, J values from detailed FE analysis based on incremental plasticity using full stress-strain data are used to predict the maximum moments^{*2}. The resulting ratios are also given in Table 3. Note that the predictions using FE J could be regarded as the most accurate ones. It can be seen that the predictions using the present

^{*2} This particular method is referred to the Option 3/Category 3 option in R6. The J values from detailed elastic-plastic FE analysis based on the initial crack length are used to construct the FAD (that is the R6 Option 3 curve). Then the tearing analysis is performed according to the Category 3 analysis in R6.

Table 2 Summary of pipe test data of circumferential through-wall cracked pipes under bending considered in the present study

Loading Type	Test I.D.	Material	$D_o=2R_o$ (mm)	t (mm)	R_m/t	θ/π	Temp. (°C)
Monotonic bending (Base metal)	4111-2	A155	711	23.6	14.56	0.37	288
	4131-7	SA333 Gr. 6	273.1	18.3	6.96	0.346	288
	4.3-1	STS-49	763.52	38.18	9.50	0.166	300
	1.1.1.21	A155	711	22.7	15.16	0.0625	288
	3.3-1	STS-410	166	14.5	5.22	0.166	300
	1.2-7	A106	168	14	5.5	0.36	288
	EPRI-1T	SA376 TP304	114.3	9.0	5.85	0.371	22
	EPRI-8T	SA358 TP304	414	26.2	7.40	0.368	22
	4131-5	SA376 TP304	158.9	13.9	5.22	0.388	288
Monotonic bending (Weld metal)	1.1.1.26	TP316L	106.2	8.3	5.90	0.244	21
	BCD/WJ-1	SA106 Gr.B	168.3	11.05	7.12	0.304	288
	1.1.1.24	SA333 Gr. 6	612	31.3	9.28	0.079	288
	4141-1	SA376 TP304	168.3	14.3	5.38	0.371	288
	4141-3	SA358 TP304	413.5	26.2	7.39	0.367	288
Cyclic bending (Base metal)	1.1.1.23	SA240 TP316L	711	30.2	11.27	0.0625	288
	1.2-2	A106 Gr. B	168	14	5.5	0.36	288
	1.2-4	A106 Gr. B	168	14	5.5	0.36	288
	3.3-2	A106 Gr. B	167.8	13.7	5.6	0.369	288
	1.2-3	SA376 TP304	169	14	5.54	0.38	288
	1.2-5	SA376 TP304	168.5	14.2	5.43	0.368	288

methods are close to, but slightly conservative than, those using FE J , which provides confidence in the accuracy of the proposed J estimates. Comparing the proposed J estimates with those based on the R6 Option 2, the proposed method gives overall less conservative results.

5. Concluding Remarks

The present work presents methods to estimate elastic-plastic J for circumferential through-wall cracked pipes for the Leak-Before-Break (LBB) analysis of pressurized piping. Proposed methods are based on the GE/EPRI approach and the key issue is to propose a robust Ramberg-Osgood fitting procedure. Two different estimation schemes are given, one for the case when full stress-strain data are available, and the other for the case when only yield and ultimate tensile strengths are available. Comparison of estimated J based on the proposed methods with those from extensive elastic-plastic FE anal-

Table 3 Comparison of predicted maximum moments according to the R6 method and the proposed method with experimental data

Test I.D.	Ratio (Predicted moment / Experimental moment)			
	Proposed (full)	Proposed (limited)	R6 (Opt. 2)	FE Result
4111-2	0.71	0.72	0.72	0.77
4131-7	0.86	0.85	0.69	0.88
4.3-1	0.66	0.64	0.66	-
1.1.1.21	0.79	0.77	0.82	-
3.3-1	0.81	0.74	0.81	-
1.2-7	0.82	0.83	0.75	-
EPRI-1T	0.93	0.89	0.82	-
EPRI-8T	0.87	0.85	0.73	0.88
4131-5	0.71	0.63	0.56	-
1.1.1.26	1.11	1.05	0.96	-
BCD/WJ-1	0.84	0.81	0.76	-
1.1.1.24	0.62	0.62	0.66	-
4141-1	0.68	0.64	0.54	0.67
4141-3	0.80	0.79	0.70	0.83
1.1.1.23	0.77	0.72	0.72	-
1.2-2	0.88	0.88	0.80	-
1.2-4	0.99	0.99	0.90	-
3.3-2	1.00	1.00	0.91	-
1.2-3	0.90	0.81	0.71	-
1.2-5	0.99	0.89	0.77	-

yses shows good agreements. Furthermore experimental validation is performed by comparing maximum moments predicted by fracture mechanics analysis using the proposed J estimates with those from full-scale pipe test. The results show sufficient confidence in the accuracy of the proposed J estimates, i.e., the proposed Ramberg-Osgood fitting procedures.

One important finding is that the J estimates based on only yield and tensile strengths are close to those based on full stress-strain data for all cases considered in the present work. Noting that tensile data are often limited in practical situation, the proposed J estimates would be very useful in elastic-plastic fracture mechanics analyses of circumferential through-wall cracked pipes for the Leak-Before-Break analysis.

The present paper considers circumferential through-wall cracked pipes under only bending loading, but for practical application, the effect of internal pressure should be incorporated. Application of the GE/EPRI approach is rather limited because plastic influence functions relevant to combined pressure and bending should be found. Once such functions are found, see for instance Rahman et al.⁽⁵⁾, the proposed Ramberg-Osgood fitting procedure would provide accurate J estimates. For the reference stress approach, on the other hand, the effect of internal pressure on elastic-plastic J estimates has been discussed elsewhere⁽¹⁰⁾, and detailed information can be obtained therein.

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