

CONSIDERATION FOR USING THE EQUIVALENT ENERGY METHOD TO PREDICT THE MAXIMUM LOAD-CARRYING CAPACITY OF CIRCUMFERENTIALLY SURFACE-CRACKED PIPES

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ABSTRACT

This study provides an energy equivalent method for calculating the J-integral of circumferentially surface cracked pipes. The proposed method, originally developed by Rahman and Brust for global bending, has been extended in this study to account for combined internal pressure and global bending. For the application of the proposed method, four key considerations are discussed – fracture toughness properties, tensile properties, equivalent wall thickness models and combined loading conditions – by comparing the estimated maximum loads with experimentally measured values. Among these, the combination of tensile curves and the J-resistance curves is identified as the most critical factor in predicting the maximum load of circumferentially surface-cracked pipes.

INTRODUCTION

Piping failure can be defined in various ways, but the worst-case scenario is a double-ended guillotine break, which must not occur during plant operation. Predicting the maximum load-carrying capacity of the piping can be an effective method to prevent catastrophic failure, and this prediction is normally based on elastic-plastic fracture mechanics.

In the context of the leak-before-break (LBB) concept (U.S. NRC, 2007), piping must not undergo fast fracture during the reactor shutdown following the detection of unacceptable leakage. The duration of crack growth, from the leakage crack to the critical crack, is crucial to ensure sufficient margin for the safe shutdown of the reactor. Since the maximum load-carrying capacity of the piping is directly related to the determination of the critical crack size, improving the accuracy of its estimation will enhance the reliability of the LBB design.

Although the deterministic LBB method assumes a through-wall crack, the probabilistic LBB method models crack growth from initiation to through-wall penetration and evaluates the potential for pipe failure at each stage of crack development. In probabilistic fracture mechanics analysis, explicit J-integral solutions are required due to the high cost of analyses. One such solution is the J-estimation method, based on equivalent energy methods such as SC.ENG, LBB.ENG, etc.

This paper outlines the considerations in using the equivalent energy method for determining the factors that affect the prediction of the maximum load-carrying capacity of circumferentially surface-cracked pipes.

J ESTIMATION BASED ON EQUIVALENT ENERGY METHODS

This paper considers a pipe with a circumferential surface crack of constant depth, as shown in Fig. 1. When a tensile load T is applied through the point O and a bending moment M is applied about the axis H , the problem can be converted into an equivalent one where the tensile load T acts through the point O' and an equivalent moment, $M + e \cdot T$ is applied about the axis, H' .

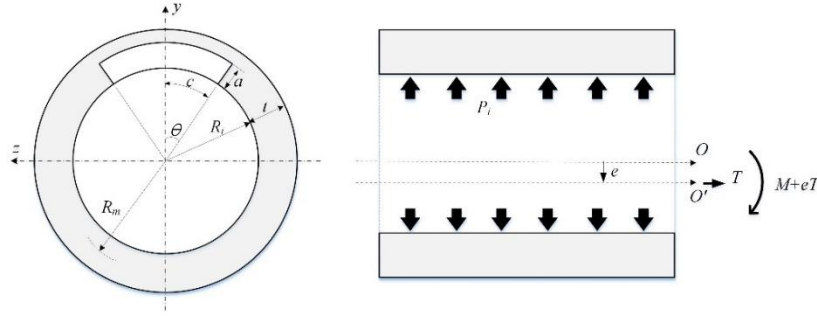


Figure 1. A schematic diagram for a surface cracked pipe under combined tension and bending moment

Brust & Gilles (1994) proposed an analytical method, known as the equivalent energy method, for predicting the J-integral for circumferential through-wall cracked pipes. Later, Rahman and Brust (1997) extended this method to circumferential surface-cracked pipes, which is referred to SC.ENG method. A summary of this method is provided below.

Circumferentially Surface-Cracked Pipes under Bending Moment

Figure 2 illustrates the concept of the energy equivalent method. It assumes a pipe with reduced section but without a crack, having the same compliance as the crack pipe.

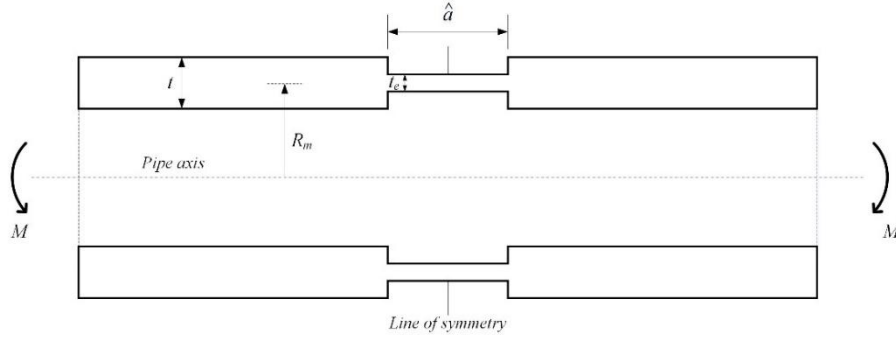


Figure 2. The energy equivalent method based on the reduced section analogy

Considering the equivalent pipe under bending moment, as shown in Fig. 2, the classical beam theory combined with Ramberg-Osgood constitutive law leads to a relationship between the elastic rotation (ϕ_e^c) and plastic rotation (ϕ_p^c).

$$\phi_p^c = \left(\frac{t}{t_e}\right)^{n-1} \cdot \left(\frac{\pi}{4R}\right)^n \cdot \alpha \cdot \left(\frac{M}{M_0}\right)^{n-1} \phi_e^c \quad (1)$$

Accordingly, the plastic part of the energy release rate can be expressed as follows:

$$J_p = \frac{\partial}{\partial A} \int \phi_p^c dM = \frac{\alpha}{n+1} \cdot \frac{2\pi\sigma_0^2}{E'} \cdot \left(\frac{\pi}{4R}\right)^n \cdot \left(\frac{M}{M_0}\right)^{n+1} \cdot \frac{\partial(I_B \cdot H_B^{n-1})}{\partial A} \quad (2)$$

$$I_B = \int a F_B^2 dA \quad (3)$$

Here, I_B represents the term related the strain energy produced by the bending moment, and it is derived from Eq. (2) using the stress intensity factor solution. F_B denotes the shape factor in the relevant stress intensity factor solution. H_B denotes the ratio of thicknesses between the cracked and uncracked pipes. The equivalent thickness, t_e , for the uncrack pipe can be determined by matching the limit loads of the cracked and uncrack pipes. Accordingly, H_B can be expressed as follows:

$$H_B = \frac{t}{t_e} = \frac{2}{2 \sin \beta - \frac{a}{t} \sin \theta} \quad (4)$$

Circumferentially Surface-Cracked Pipes under Combined Internal Pressure and Bending Moment

Internal pressure acting on a pipe with a circumferential surface crack can be treated as a tensile load. As Brust and Gilles (1994) derived the energy release rate under tensile loading for a pipe with a circumferential through-wall crack using the equivalent energy method, the energy release rate due to tensile loading can also be derived for a pipe with a circumferential surface crack. Similar to the derivation of the relationship between elastic and plastic rotations under bending moment, the relationship between elastic and plastic displacements (δ_e^c and δ_p^c) due to the tensile load, T , can be expressed as follows:

$$\delta_p^c = \alpha \cdot \left(\frac{\sigma_m}{\sigma_0}\right)^{n-1} \cdot \left(\frac{t}{t_e}\right)^{n-1} \cdot \delta_e^c \quad (5)$$

Here, α and σ_0 are Ramberg-Osgood parameters and σ_m represents membrane stress. Accordingly, the plastic part of the energy release rate can be expressed as follows:

$$J_p = \frac{\partial}{\partial A} \int \delta_p^c dT = \frac{\alpha}{n+1} \cdot \frac{2\pi\sigma_0^2}{E'} \cdot \left(\frac{T}{T_0}\right)^{n+1} \cdot \frac{\partial(I_T \cdot H_T^{n-1})}{\partial A} \quad (6)$$

$$I_T = \int a F_T^2 dA \quad (7)$$

Here, I_T represents the term related the strain energy produced by the tensile load, and it is derived from Eq. (2) using the stress intensity factor solution. F_T denotes the shape factor in the stress intensity factor solution for tensile load. The stress intensity factor solution used in this paper was taken from ASME BPVC Section XI (2017) Appendix C, C-431. H_T denotes the ratio of thicknesses between the cracked and uncracked pipes. Similar to the case under bending moment, the equivalent thickness, t_e , for the uncrack pipe can be determined by matching the limit loads of the cracked and uncrack pipes. In this paper, the limit load solution proposed by Schulze et al. (1980) was used. Accordingly, H_T can be expressed as follows:

$$H_T = \frac{t}{t_e} = \frac{1}{1 - \frac{a\theta}{t\pi} - \frac{2}{\pi} \sin^{-1}\left(\frac{1a}{2t} \sin \theta\right)} \quad (8)$$

In addition, the eccentricity e , as shown in Fig. 2, can be expressed as follows:

$$e = R_m \cdot \sin\left(\frac{\theta(\pi-\theta)\frac{a}{t}}{2(\pi-\theta\frac{a}{t})}\right) \quad (9)$$

SUMMARY OF EXPERIMENTAL TESTS

The pipe fracture tests used for comparison with the predicted maximum loads in this study were referenced from NRC documents (Scott, 1987; Scott et al., 1987 & 1994; Wilkowski et al., 1989). For ferritic steel pipes, a total of eight experimental results under pure bending and four under combined internal pressure and bending were collected. These include three NPS 6, three NPS10 and two NPS 16 pipes. For austenitic stainless steel pipes, a total ten experimental results were gathered, including nine NPS 6 and one NPS 16 pipes. In all test, the ratio of crack depth to thickness (a/t) is approximately 0.65, and the normalized crack length (θ/π) ranged from 0.12 to 1.0. For ferritic steel pipes under combined loading, internal pressures ranged from 15.5 MPa to 18.3 MPa, while for austenitic stainless steel pipes, they ranged from 7.9 MPa to 39.3 MPa. All tests were conducted at 550 °F.

Figure 3 shows the experimental results under global bending. For ferritic steel pipes under global bending, the maximum bending moments ranged from 0.5 to 0.62 relative to the limit moment of the corresponding uncrack pipes. For austenitic stainless steel pipes under global bending, the maximum bending moments ranged from 0.5 to 0.7 relative to the limit moment.

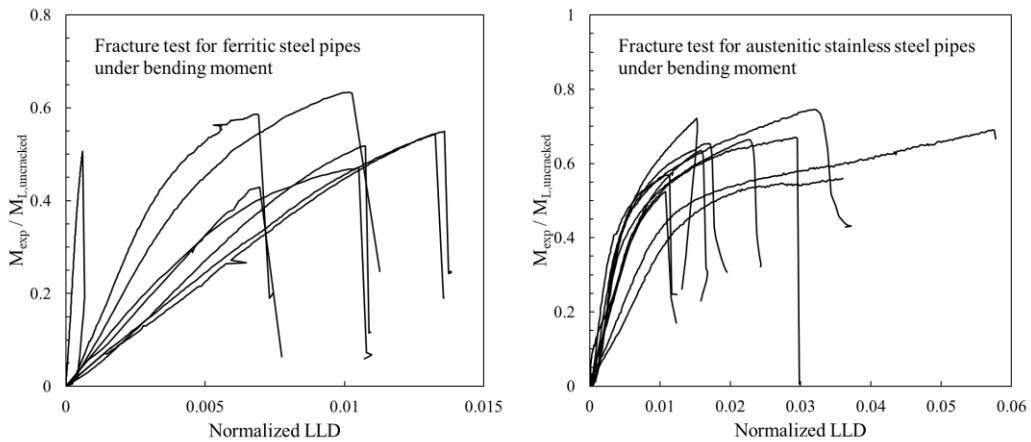


Figure 3. Pipe fracture test results under bending moment

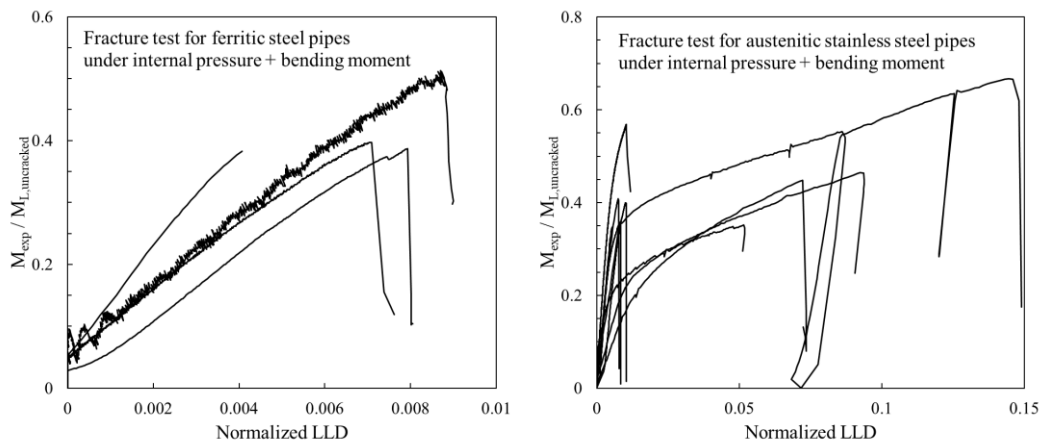


Figure 4. Pipe fracture test results under combined internal pressure and bending moment

Figure 4 shows the experimental results under combined internal pressure and global bending. The maximum bending moments under combined loading are relative lower than those observed under global bending.

CONSIDERATION OF THE PROPOSED METHOD

In this study, pipe fracture is evaluated using the Crack Driving Force Diagram (CDFD) method, which is based on elastic-plastic fracture mechanics. The CDFD method predicts unstable crack growth by comparing the experimental J-resistance curves of the material with the J-integral at the crack tip.

$$J_{app} = J_{mat} \quad \text{and} \quad \frac{\partial J_{app}}{\partial a} \geq \frac{\partial J_{mat}}{\partial a} \quad (10)$$

Due to inherent uncertainties in material properties and J-integral estimation methods, it is necessary to investigate their impact on the pipe's estimation of the maximum load-carrying capacity.

Fracture Toughness Properties

The J-resistance curves of a material is determined through fracture toughness testing. However, even for the same material, repeated tests often show significant variation in results. Therefore, the predicted maximum load of a pipe can vary depending on which J-resistance curve is used.

Figure 3 compares the predicted maximum loads using a J-resistance curve obtained from a single specimen and another obtained by averaging the results from multiple specimens of the same material specification. It should be noted that having the same material specification does not imply that the specimens were taken from the same pipe product; the multiple specimens were not sampled from a single product. It is observed that the use of the averaged J-resistance curve leads to more accurate predictions of the pipe's maximum load.

Figure 4 illustrates the influence of specimen orientation. For both ferritic steel pipes and austenitic stainless steel pipes, the predictions using the J-resistance curve from L-R specimens show good agreement with experimental results. Moreover, when the J-Resistance curve from L-C specimens is used, the predicted maximum loads are more conservative compared to those obtained using L-R specimens. It is also noted that austenitic stainless steel pipes are less affected by the specimen orientation than ferritic steel pipes.

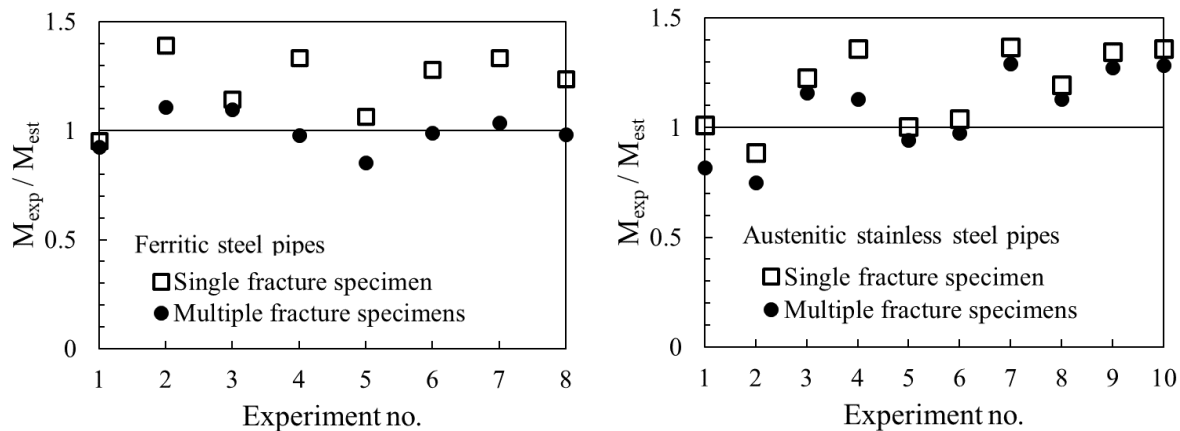


Figure 5. Comparison of predicted maximum loads using different J-resistance curves

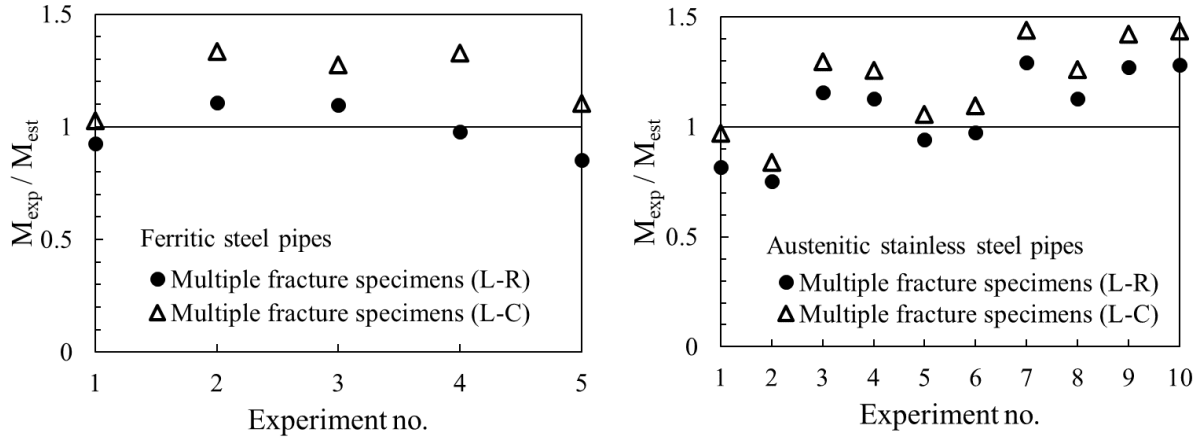


Figure 6. Influence of specimen orientation on the predicted maximum load

Tensile Properties

When predicting J-integral using the energy equivalent method, a tensile curve expressed by the Ramberg-Osgood constitutive law is required, which is obtained through tensile testing. Unlike fracture toughness tests, tensile tests exhibit good reproducibility, and similar tensile curves are generally obtained even after multiple tests.

Figure 5 compares the predicted maximum loads using a tensile curve obtained from a single specimen and another obtained by averaging the results from multiple specimens of the same material specimen. It is observed that using the tensile curve from a single specimen provides more accurate predictions of the maximum load for ferritic steel pipes compared to the averaged curve. This suggests that the uncertainty in tensile curves is relatively low, and using averaged curves from specimens taken from various products may introduce additional variability.

In contrast, for austenitic stainless steel pipes, the influence of the two tensile curves appears negligible. This trend is consistent with the earlier observation that austenitic stainless steel pipes are less sensitive to variation in crack resistance curves compared to ferritic steel pipes.

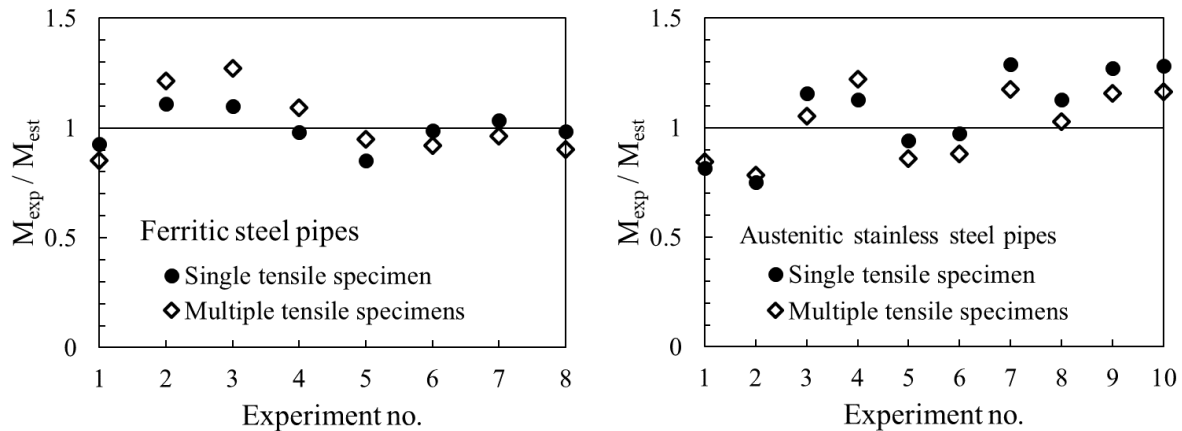


Figure 7. Comparison of predicted maximum loads using different tensile properties

Equivalent Wall Thickness Models

SC.ENG, proposed by Rahman and Brust (1997), provides two approaches for explicitly predicting the J-integral: one based on a global limit load solution (SC.ENG1), and the other on a modified limit load solution (SC.ENG2). The modified limit load solution reduces the original global limit load, resulting in a smaller equivalent thickness (t_e) compared to SC.ENG1. Consequently, the J-integral predicted by SC.ENG2 is larger than that predicted by SC.ENG1. According to the original paper, the modified limit load solution better accounts for the local ligament near the surface crack, and thus the J-integral predicted by SC.ENG2 agrees more closely with finite element analysis (FEA) results. However, local failure near the surface crack does not necessarily lead directly to pipe fracture, and unlike through-wall cracks, which grow in a one-dimensional fashion, surface cracks propagate in a two-dimensional manner. Therefore, in terms of predicting the maximum load, the J-integral that represents the load-carrying capacity of the entire pipe cross-section is more relevant.

Figure 6 compares the predicted maximum loads based on different energy equivalent methods. It is observed that the predictions based on SC.ENG1 show better agreement with the experimental results. The predictions based on SC.ENG2 are more conservative, particularly in the case of ferritic steel pipes. These findings are consistent with the previously reported observation that SC.ENG2 predicts larger J-integral values than SC.ENG1. Therefore, for predicting the maximum load of a pipe using the energy equivalent method, the global limit load solution is considered more appropriate.

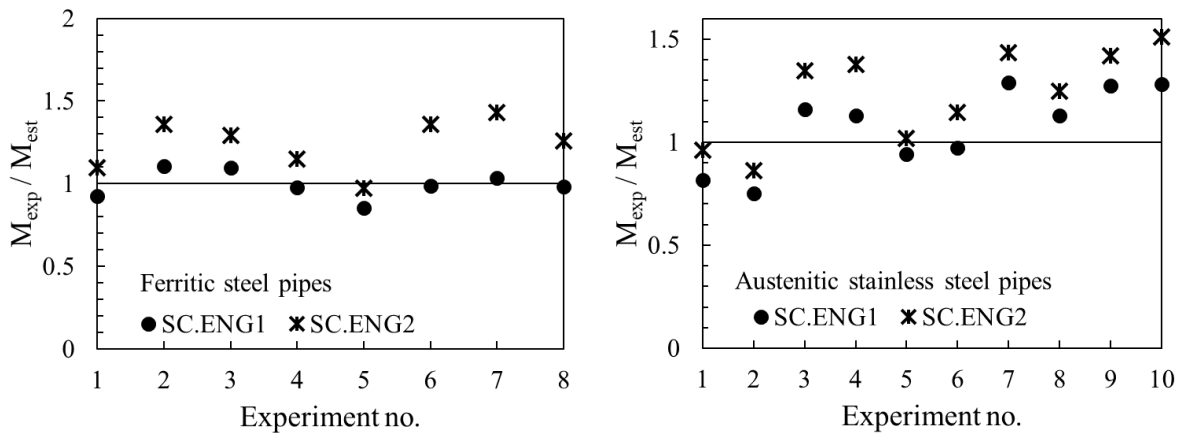


Figure 8. Comparison of predicted maximum loads using different energy equivalent methods

Combined Loading Conditions

Piping systems are typically subjected to various loads, such as internal pressure, thermal expansion, and more. In inelastic fracture mechanics, there is no simple way to consider the effects of combined loading conditions, except for the plastic limit envelope based on plastic hinge analysis. Plastic limit envelope (Jirasek et al., 2002) provides a relationship between tensile and bending loads and their contribution to the plastic deformation of the structural member. This approach is generally recognized as an effective alternative for considering combined load effects in elastic-plastic fracture mechanics evaluations.

This study proposes a method for predicting the J-integral based on the energy equivalent method when internal pressure and global bending act simultaneously. To validate the proposed method, it was compared with the plastic limit envelope, as shown in Figure 7. The proposed method predicts the maximum load of the pipe slightly more conservatively than the plastic limit envelope and shows better agreement with the experimental results. Therefore, the proposed approach is considered appropriate for predicting the maximum load of pipes under combined loading conditions.

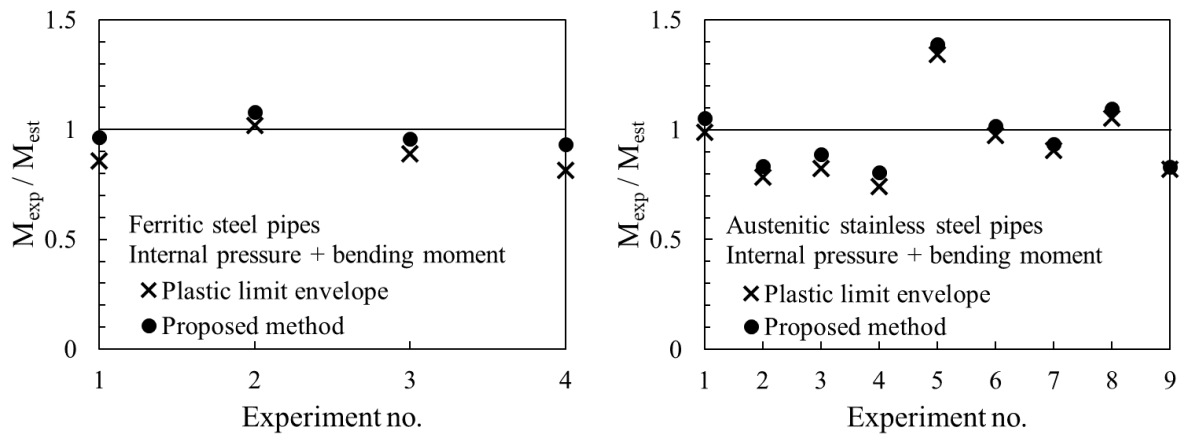


Figure 9. Comparison between the proposed method and plastic limit envelope for predicting maximum loads of circumferentially surface-cracked pipes under combined loading

CONCLUSION

This study presents an energy equivalent method for predicting the J-integral of circumferentially surface cracked pipes subjected to combined internal pressure and global bending. Key considerations in the application of the proposed method are discussed, with comparison to experimentally measured maximum bending moments. The results indicated that material properties – such as the tensile curve and the J-resistance curve – are among the most influential factors. Using the tensile curve from a single specimen provided more accurate predictions of the maximum load for ferritic steel pipes compared to using the averaged curve, whereas the use of an averaged J-resistance curve resulted in better agreement with experimental maximum loads. Furthermore, the orientation of the fracture toughness specimens had a greater impact on ferritic steel pipes. In contrast, austenitic stainless steel pipes were found to be less sensitive to these material property variations. Addressing these considerations can enhance confidence in structural integrity assessment of surface-cracked pipes.

ACKNOWLEDGEMENTS

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