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A Simple Method for Estimating Effective J-Integral in LBB Application to Nuclear Power Plant Piping System

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ABSTRACT

This paper suggests a simple method to estimate the effective J-integral values in applying Leak-Before-Break (LBB) technology to nuclear piping system. In this paper, the effective J-integral estimates were calculated using energy domain integral approach with ABAQUS computer program. In this case, there existed a apparent variation of J-integral values along the crack line through the thickness of pipe. For this reason, several case studies have been performed to evaluate the effective J-integral value. From the results, it was concluded that the simple method suggested in this paper can be effectively used in estimating the effective J-integral value.

1. INTRODUCTION

Recently, LBB concept has been applied extensively to high energy piping systems in neclear power plants (NPP). LBB application to NPP piping system can be evaluated by stability assessment based on the elastic plastic fracture analysis (EPFA), which evaluates the fracture behavior of cracked pipe. EPFA is used to predict if a defect or crack in a piping will grow when the piping is loaded, possibly leading to failure of component. It involves the determination of the J-integral which is the change in mechanical energy per unit area of new crack surface. The J-integral can be used in predicting crack propagation.

For three-dimensional (3-D) problems, two approaches are currently used to calculate J-integral. These are virtual crack extension and energy domain integral method. Park [1] and Hellen [2] formulated the virtual crack extension approach in terms of finite element stiffness and displacement matrices. deLorenzi [3,4] improved the virtual crack extension method by considering the energy release rate of a continuum approach. Shih, et, al [5,6] have recently formulated the energy domain integral methodology which is a general framework for numerical analysis of J-integral.

However, in case of using the *J-INTEGRAL option in ABAQUS computer code [7] which adopts energy domain integral technique, there exist an apparent variation of J-integral value along the crack line of 3-D through-wall cracked (TWC) pipe. Clearly, maximum J-integral value is obtained at the center of the crack line (mid-thickness of pipe) under combined loading including pressure, tension, and bending moment. The J value can be simply selected since it is the largest one under this loading condition. However, this is too conservative for predicting maximum load of a pipe in evaluating LBB application to NPP piping systems. Because the J-integral can be used to predict the initial load which corresponds to initiation of crack growth in a pipe. Therefore, it is very important to select which one of J-integral values varied through pipe wall in order to reduce excessive conservatism.

Accordingly, several case studies have been performed to evaluate the effective J-integral value in this paper. Firstly, the variations of J values through the thickness of TWC pipe were investigated under several loading conditions. Secondly, the maximum loads predicted from the methods presented in this paper were compared with the maximum experimental loads from the IPIRG program test [8] and the various predictable methodologies in fracture analysis. This is to verify the finite element analysis (FEA) method and to determine reasonably the simple method for calculating the effective J-integral value. Also, the independent review has been performed to assure the validity of method presented in this paper by using virtual crack extension method.

2. VARIATIONS OF J-INTEGRAL ALONG THE THICKNESS OF TWC PIPE

EPFA had been conducted for straight circumferential TWC pipe using ABAQUS [7], generalized nonlinear FEA computer program. FEA element was 20 node isoparametric. Since the pipe has two planes of geometric symmetry one quarter of the pipe is modeled as shown in Fig. 1. In the 3-D model of FEA, pipe wall is devided into several layers in the radial direction as shown in Fig. 2 in oder to investigate the variation of J-integral values. In applying pressure loads, the tensile load is considered to simulate the effects of pressure at endcap, while internal pressure of 15 MPa (2,250 psi) on inside surface of pipe and its half on cracked faces are considered. In applying loads to FEA model, the loads due to internal pressure were applied first, followed by increasing bending moment. The material properties used in FEA were taken from the PIFRAC [9] data base which contains SA106B carbon steel and SA312 stainless steel.

The results of the analyses indicate that there existed a variation of J along the crack line through the thickness of pipe. Fig.3 (a) shows the variation of normalized J (normalized with respect to the J value at the inner surface) as a function of the normalized distance from the inner wall (normalized with respect to the wall thickness) for the combined load. The maximum J values for all models meshed as shown in Fig.2 (a), (b), and (c) are obtained from the mid-point of pipe wall along the crack line as shown in Fig.3 (a). Also, the J-integral was checked for various contours, since it should be path independent. There was normally a small variations in the values of J calculated for the five contours as shown in Fig. 3 (b). Three contours except for the crack line and second contour are valid because the values of J-integral for these contours are similar.

In addition, the variation of J due to pressure at cracked face was investigated for a small diameter pipe with TWC of up to 140 degree in the circumferential direction. Fig. 4 shows that the value of J with the effect of pressure at cracked face is much larger than that without its effect. The magnitude of this difference is proportional to the increase in applied loads as shown in Fig. 4. Therefore, it is judged that the effect of pressure at crack faces as well as at endcap be considered.

3. EFFECTIVE J-INTEGRAL VALUE

In 3-D fracture evaluation of TWC pipe using ABAQUS computer program[7], the variations of J-integral values occur apprently along the crack line through the thickness of pipe as shown in Fig. 3 (a). Maximum J is obtained at the center of crack line (mid-point of pipe thickness) under the applied loads described in the above. However, it is very conservative to use the J value at mid-thickness in predicting maximum load for LBB evaluation. The reason is that the maximum J is much higher than the other as shown in the Fig. 3 (a) and can be used for predicting initial load. Hence, it is very important to determine the representative value of J-integral that can be applied for predicting maximum load of the 3-D TWC pipe.

The representative J value is expected to distribute in the range between 1.5 and 2.5 of the normalized constant (J/J_{inner}) shown in Fig. 3 (a). For this reason, the combination methods of the J values are reviewed as follows:

$$\text{CASE 1} = (J_{OUTER} + J_{MID} + J_{INNER}) / 3$$
$$\text{CASE 2} = (J_{OUTER\_MID} + J_{MID} + J_{INNER\_MID}) / 3$$
$$\text{CASE 3} = (J_{OUTER} + J_{OUTER\_MID} + J_{MID} + J_{INNER\_MID} + J_{INNER}) / 5$$
$$\text{CASE 4} = J_{MID}$$

For the review of each combination, it is necessary to perform stability assessments and compare instability loads with the results of an pipe test for TWC pipe.

During the course of the IPIRG-2 program, 6-inch and 16-inch nominal diameter pipe fracture experiments were conducted by Battelle [8]. The 6-inch diameter pipe was tested under the conditions of single dynamic, monotonic, pressurized TWC pipe experiment. 16-inch diameter pipe was tested under the conditions of quasi-static, monotonic, four-point bend, short TWC pipe. Fig. 5 shows the schematic illustration of the piping test. The key results from these test conditions are represented in Table 1. Both experiments were conducted at the test temperature, 288°C and test pressure, 15.5 MPa (2,250 psi) to consider the nuclear piping operational conditions. For each actual pipe experiment, the crack initiation load and the maximum load were measured.

The FEA model shown in Fig.1 was used to simulate Battelle pipe test. The instability loads was calculated by using the J-integral / Tearing modulus (J/T) method with respect to the described combinations above. Fig. 6 shows the material properties for the pipes used in the finite element analysis. These properties were taken from material test during IPIRG-2 program.

In order to discuss and determine the effective J-integral value for each pipe size, the maximum experimental loads from the IPIRG-2 pipe experiments [8] can be compared with analytical predictions from various fracture analyses based on Ref [8] and from the combinaton methods presented in this paper. The comparison shows that the instability load calculated from CASE 1 can be reasonably and conservatively predicted as shown in Fig. 7.

In addition, the J-integral values calculated from CASE I was confirmed by independent review. This was done by using virtual crack extension method. In this method, each J-integral was calculated by applying a virtual displacement to specified node as shown in Fig. 8 (a) through (d). Mean value of J-integral for four cases in Fig. 8 was used to predict the maximum load by using J/T method. For performing a independent review, 12-inch, sch 160, stainless steel pipe based on Ref [10] is selected as an example. The key results of FEA is indicated in Table.2. The difference between the methods for predicting the instability load of a TWC pipe is found to be very small (about 5%). Therefore, it is suggested the effective J-integral value be obtained by the combination of CASE 1.

4. CONCLUSION

The effective J-integral estimates could be very effectively and conservatively obtained from the presented combination of J values for 3-D through-wall cracked pipe using energy domain integral approach, which ABAQUS computer program [7] adopts with *J-INTEGRAL option. The simple method suggested herein, therefore, can be used in performing LBB evaluation by using only uniformed two layers without considering configurations of various meshed elements through the thickness of pipe. This is able to be very helpful in the LBB analysis for NPP piping system. As a further work, it is thought that the method presented should be extended to nozzle-pipe interface as well.

5. REFERENCE

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Table.1 Key results for 6 and 16 inch pressurized TWC pipe experiments from IPIRG-2

Experiment No	Pipe Material	Outside Diameter (mm)	Pipe Thickness (mm)	Crack Length (θ/π)	Loading Rate (mm/sec)	Maximum Load (kN-m)
I-9	A106B	168.9	11.2	0.249	108	54.3
I-8	A106B	399.3	26.2	0.12	600	1038

Table.2 Summary results of independent review

TWC angle (degree)	Maximum load from Effective J-Integral (kN-m)	Maximum load from Virtual crack extension (kN-m)	Difference (%)
70°	436	452	4.1
140°	154	162	5.2

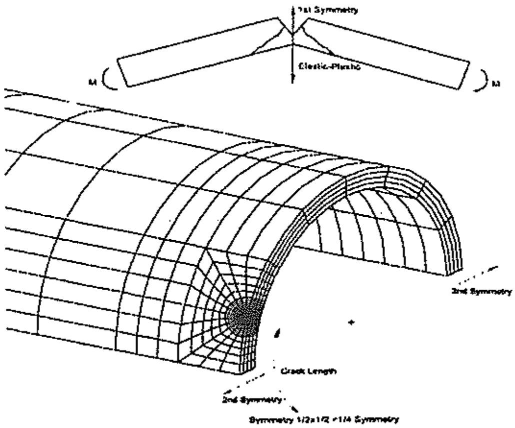
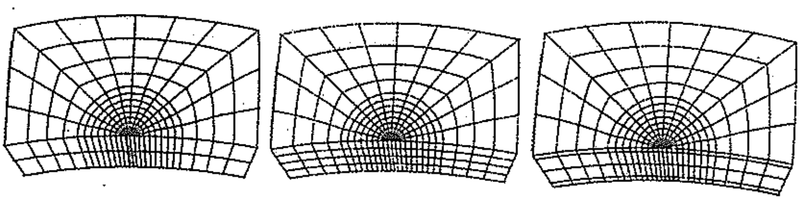
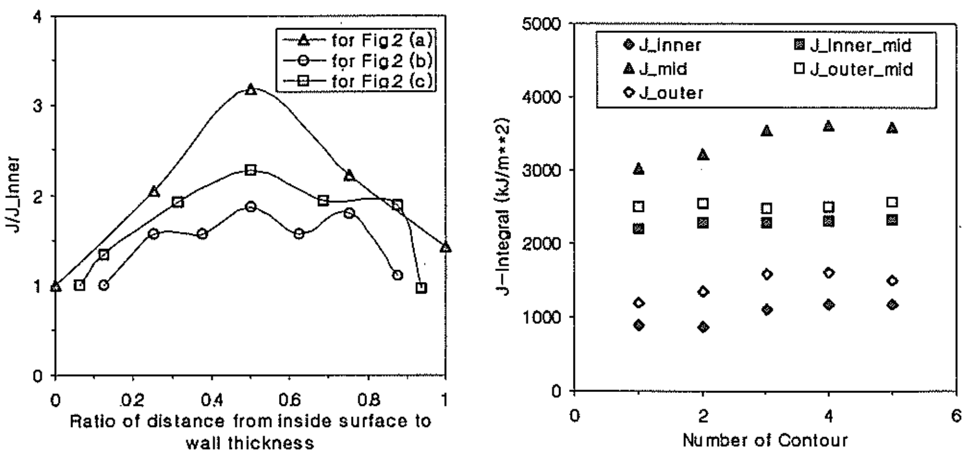


Fig.1. Symmetric finite element model at crack tip



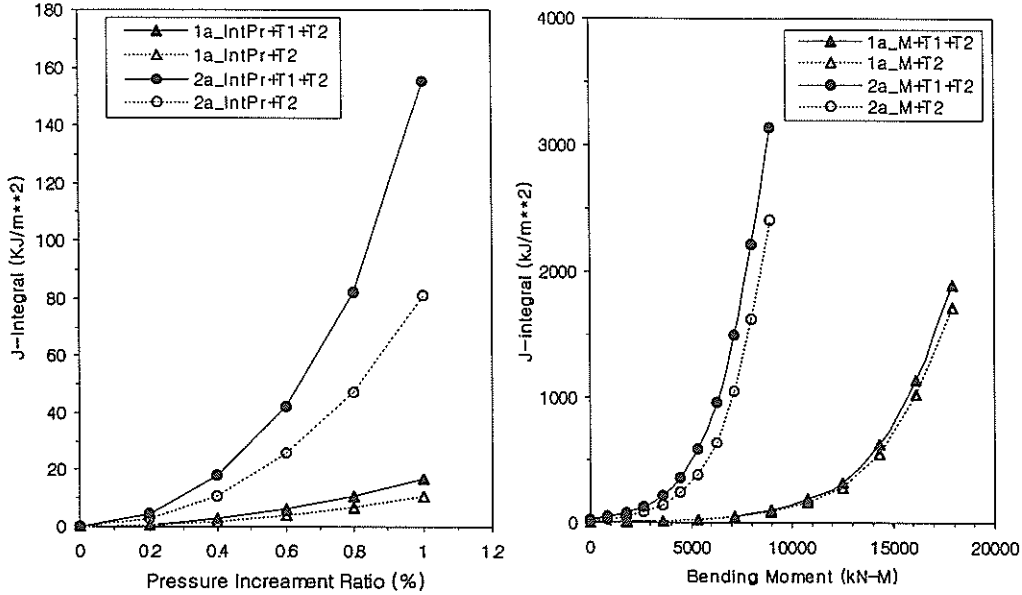
(a) (b) (c)

Fig. 2. Finite element mesh at crack tip, for (a) uniform two layers, (b) uniform four layers , (c) two way biased four layers



(a) (b)

Fig.3. Variations of J through thickness of TWC pipe along the crack line for (a) various layers, (b) several contours in uniform two layers



(a) (b)

Fig.4. Variation of J with combined load for different crack length 1a=70°, 2a=140° , M=Bending Moment, IntPr : Internal pressure 15Mpa, T1 : Pressure (at cracked faces), T2 : Tension(at endcap),(a) : J-integral vs. Load, (b) : Load in each step

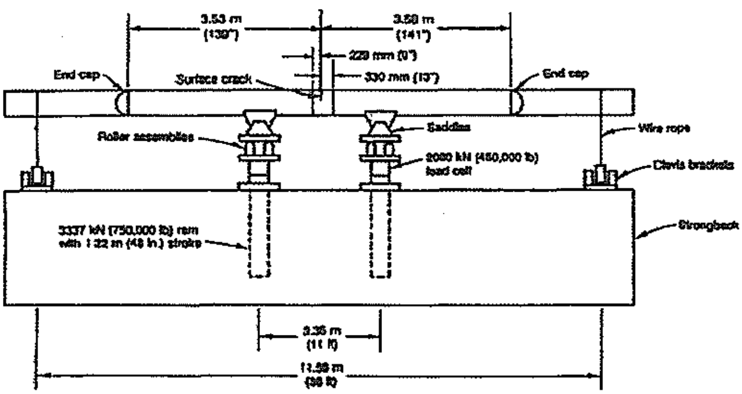
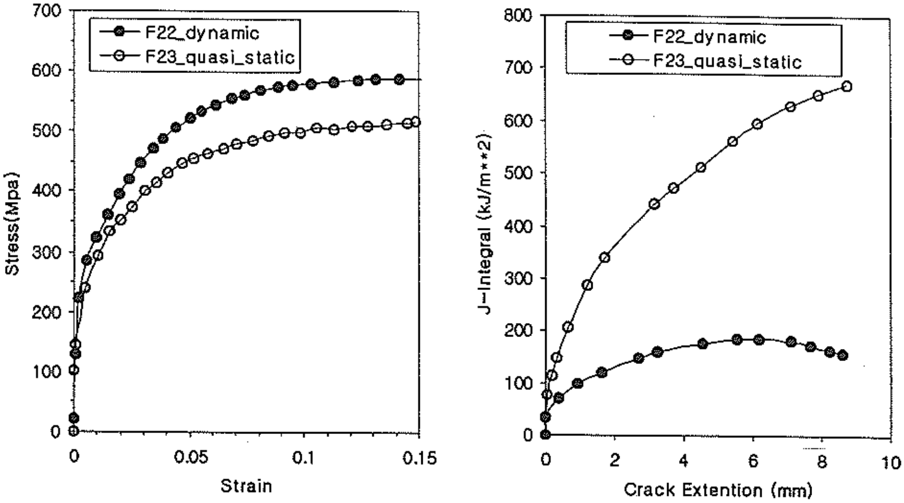


Fig. 5 Schematic of test frame used in pipe bending fracture experiment



(a) (b)

Fig.6 Material data curve for A106B, 6 (F22) and 16 (F23) inch :
(a) Engineering stress strain curve (b) J-R curve

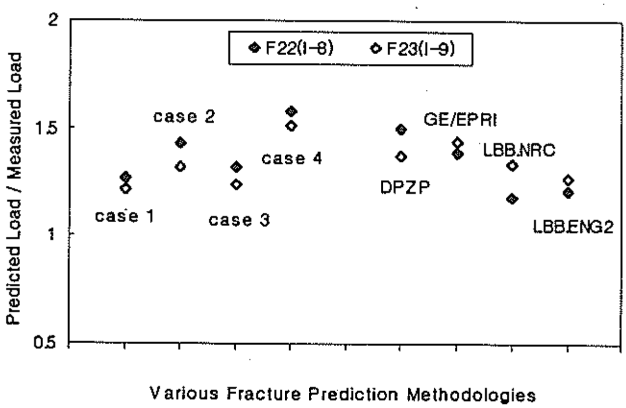
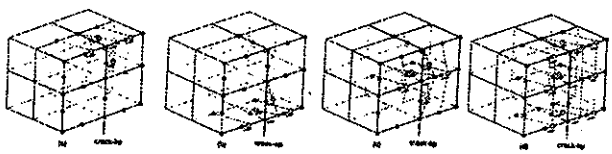


Fig.7. Results of maximum load ratios for F22(6-inch) and F23(16-inch) TWC experiments



(a) (b) (c) (d)

• : move 1 unit o : move 1/2 unit

Fig.8 Virtual crack extension along a three dimensional crack front