ELASTIC-PLASTIC FRACTURE ANALYSIS OF CIRCUMFERENTIAL TROUGH-WALL CRACKED PIPES UNDER COMBINED BENDING AND TENSION

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ABSTRACT

Using the elastic-plastic fracture mechanics (EPFM) procedure called J-integral versus tearing modulus analysis (J-T), a methodology is proposed to carry out analysis of circumferential through-wall cracked pipes under combined bending and tension. Numerical examples are presented to illustrate the proposed method. Comparisons of results with experimental data from the literature indicate the level of accuracy.

INTRODUCTION

The fracture mechanics analysis of cracked pipes is an important step in the instability evaluation of high-energy lines of nuclear power plants in a leak-before-break (LBB) program. The systems of a nuclear facility for which LBB is generally applied must be made of ductile materials. Ductile fracture mechanics' methods employ analytical techniques. These analytical techniques extend from elaborate finite element models (FEM) to various elastic-plastic fracture mechanics (EPFM) estimation procedures, such as J-integral versus tearing modulus (J-T) [1]. Also from deformation plasticity failure assessment diagram (DPFAD) [2] to simple limit load (LL) [1] and local flow stress (LFS) analyses [3]. FEM analyses are expensive and very time consuming. The purpose of simplified methodologies is to ease the performance of the analyses in terms of time and cost.

Although all simplified methods are based on the extent of the theory, it is necessary to include certain idealizing assumptions related to crack shapes, consistent crack geometry, and crack behavior. The crack behavior assumption presupposes that the crack initiates and grows as a result of increasing loads. Also, under most circumstances, it is necessary to obtain other material property data than those of the component being evaluated.

In reality, however, actual flaws may assume complex shapes. For example, the component under evaluation may deform under high loadings, particularly in the vicinity of the flaw (e.g., a pipe may ovalize and its wall may become thinner near the flaw). Also a growing crack may develop shearing lips. These facts together with the inherent variability of the material properties from specimen to specimen lead to a simple and obvious conclusion: perfect correspondence between analytical and experimental results should not be expected at all. On the other hand, to make analytical methods always useful, such methods should be able to predict results within an acceptable uncertainty band which can then be accounted for by appropriate margins.

In this paper, evaluations of circumferential through-wall cracked pipes under bending and tension, using J-T analysis, are performed. An in-house computer code was developed to conduct the assessment of crack stability. The results obtained from J-T analysis are also compared with experimental data available in the literature. At the end of the paper, some comments and conclusions are addressed based on the comparison of results .

EPFM J-T ANALYSIS

The EPFM is based on the concept of J-integral. The parameter J is employed to characterize the crack initiation and extension in ductile materials. The circumferential through-wall crack instability in pipes is predicted by J-T analysis, an approach presented in [1]. According to this reference, from the J-resistance curve obtained from fracture specimens tests (relationship between J and crack extension Δa), it is possible to compute the J-T curve for the material. The crack driving force in terms of the applied parameter J and the tearing modulus T is calculated for the initial crack length as a function of the loading. The intersection of this curve and the J-T curve, for the appropriate material, gives away the instability value of J, defined as J_{inst}. The value of J_{inst}, in a plot of the parameter J versus the load, provides the associated instability load value.

The J-T analysis procedure, represented in Figure 1, can be detailed as following. From the J-resistance curve for the material, showed in Figure 1a, it is possible to find a correlation between J_{mat} and Δa as expressed in the equation below:

$$J_{mat} = c\Delta a^{m} \tag{1}$$

where c and m are curve fitting constants which are determined in an empirical way. From Figure 1a, it is possible to get the J-integral at the initiation of the crack growth, J_{Ic}. In addition, the material tearing modulus as a function of Δa can be defined as:

$$T_{mat} = \frac{dJ}{da}\frac{E}{S_f^2} \tag{2}$$

where E is the Young's modulus, and S_f is the flow stress. For the appropriated material, the plot of J-T assumes the shape shown in Figure 1b.

The J-T curve, for the applied loads in piping with through-wall crack, can be computed from the parameter J expressed in the following form:

$$J_{app}(a) = J_e(a) + J_p(a) \tag{3}$$

In Eq. (3), $J_e(a)$ and $J_p(a)$ are the J-integral in the elastic and plastic regimes, respectively. They are available in [1]. These values are functions of the loadings (axial and/or moment), the crack dimension $(\theta = a / R)$, the pipe geometry parameter (R / t), and also the material properties from stress-strain curve (E, S_y, Ramberg-Osgood parameters).

The applied tearing modulus T_{app} is evaluated with Eq. (2) with dJ calculated from Eq. (3), as the variation of the computed $J_{app}(a)$ and $J_{app}(a + \Delta a)$. For small crack growth the applied J-T curve is a straight line. Such line is obtained connecting the origin of the J and T axis with the point P defined by $\left(J_{app}, T_{app}\right)$. As illustrated in Figure 1b, the parameter J, at instability of the crack, is identified as J_{inst}. The value of J_{inst} may be obtained from the intersection of the J-T curve, for the material, and the pertinent straight line representing the applied J-T.

The load at instability corresponding to J_{inst} can be evaluated from Figure 1c which is a plot of $J_{app}(a)$ as a function of normalized applied load.

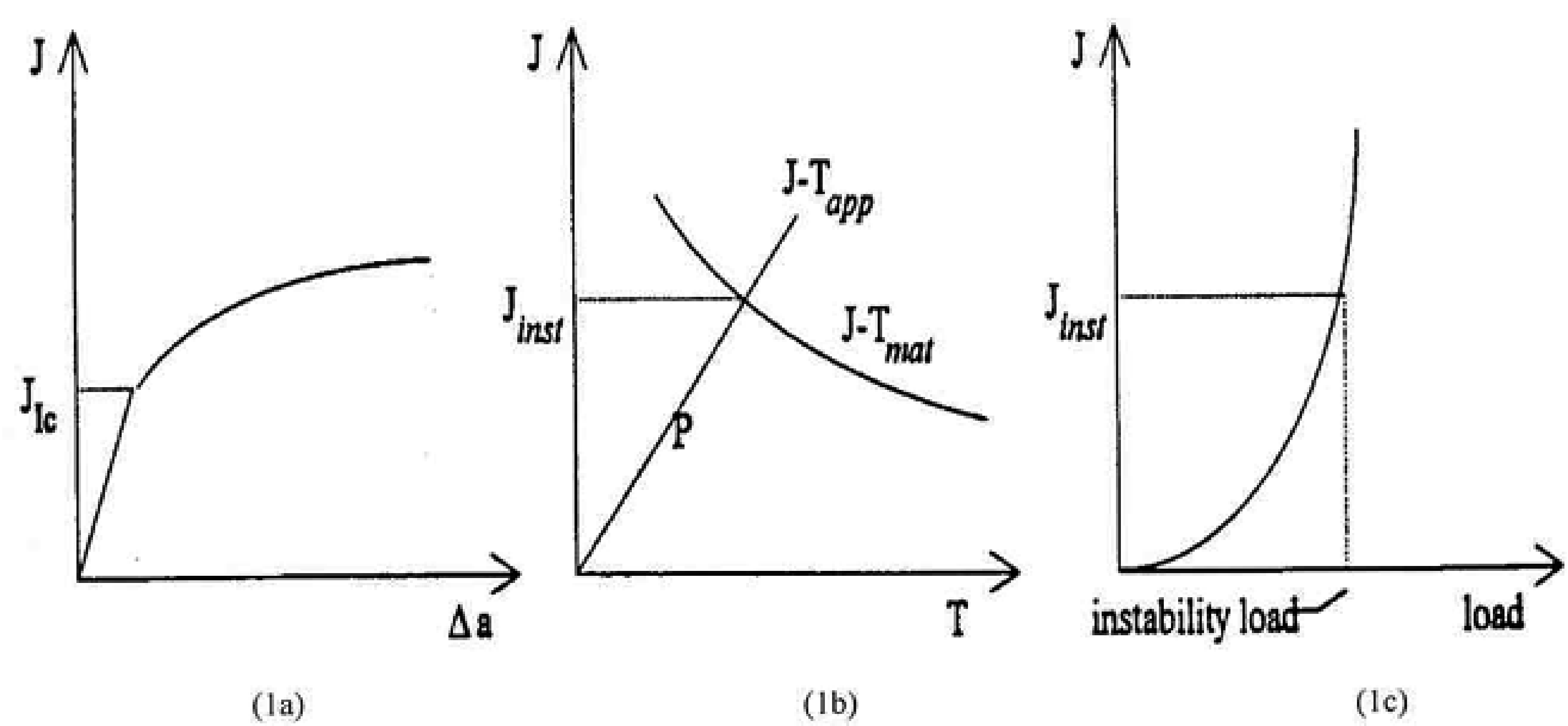

Figure 1 - Crack instability evaluation (J-T analysis procedure)

RESULTS

Tests are performed in order to assess the integrity of cracked pipes and validate the analysis methods. In Brazil, all the experimental data are referred to J-resistance curve evaluation and, at the moment, the results from the integrity tests are not yet available. Therefore, the approaches considered in this work to evaluate crack stability will be compared with the results from tests conducted in other countries and available in the literature.

Before presenting the results, it is important to notice that some information were inferred so that the material properties and the parameters required to perform the analyses were acquired. The reason for that is that, unfortunately, some data were not available in the test references. The material data information source used in this paper were [1], [4], [5]. In order to infer the material properties and corresponding parameters, some recommendations of [6] are followed. They are summarized as:

a.) range of stress-strain curve that must be fitted to ensure proper results will vary with pipe and crack geometries. To define appropriate Ramberg-Osgood parameters, it was determined that strains of 1 percent and less comprised the region of interest for the ferritic steel pipe tests, while the appropriate strain for the stainless steel pipe test condition ranged from about 2 to 8 percent;

b.) material resistance to ductile crack extension should be based on a reasonable lower-bound estimation of the material J-resistance curve;

c.) fracture toughness specimens having approximately the same thickness as the pipe wall, and without side grooves, tend to model actual pipe behavior most accurately;

d.) J-integral computational method has certain limits of applicability. Limitations are related to certain assumptions regarding the stress-strain conditions in the region near the crack tip. It is necessary to extrapolate the J-resistance curve in J-T space when those limitations are exceeded.

To combine bending and tension in the EPFM analysis it is necessary to do some assumptions to simulate the non-linear material behavior. The loading sequence must be realistic, since the superposition gives wrong results. Thus, we assume that the internal pressure is applied first, and, after, the external moments.

The obtained results and comparisons are shown in Table 1.

TABLE 1: Analytical versus Experimental Results. Through-Wall Circumferential Cracked Pipes under Combined Bending and Tension

Tests[a]	K8	K9	S4	R2	R3	R4	R5
Do (in)	4.88	4.88	31.5	16.81	16.81	16.	27.5
t (in)	0.337	0.337	1.85	0.63	0.63	0.394	1.858
Material	SS304	SS304	NiCrMo Special Melt	ferritic bainitic St	ferritic bainitic St	ferritic bainitic St	bainitic St
Angle (2θ)	76^o	135^o	60^o	90^o	45^o	60^o	60^o
Internal Pressure (psi)	2495	1049	2175	1160	1160	1160	2175
MExp Init[b] (lbf in)	-	-	-	3.717E6	7.966E6	3.664E6	-
MExp Inst[c] (lbf in)	1.221E5	8.348E4	4.868E7	7.028E6	1.133E7	4.903E6	4.868E7
MJ-T Init[d] ÷ MExp Init	-	-	-	0.59	1.11	0.59	-
MJ-T Inst[e] ÷ MExp Inst	0.88	0.80	0.43	0.34	0.79	0.47	0.57

a. Tests: K8 and K9 from [7], S4 from [8],and R2 to R5 from [2]
b. MExp Init: Experimental initiation moment
c. MExp Inst: Experimental maximum moment (failure of the pipe)
d. MJ-T Init: Initiation moment from J-T analysis
e. MJ-T Inst: Instability moment from J-T analysis

CONCLUSIONS AND COMMENTS

The method used in this paper is an "engineering approaches" based on fracture mechanics with assumptions related to crack shape, consistent geometry, crack behavior, load types and load combinations, material properties and parameters. In some cases, there was a good consistency between the analytical results and the experimental ones. In other cases, the harmony was not so good. The consistencies might be function of the adjustment of some parameters and hypotheses adopted.

In general, the results show that the analytical method gives initiation and instability loads smaller than the experimental methods. There is a good agreement between analytical and experimental results where the material properties and the parameters are defined in a more accurate way. It is meaningful to emphasize that material data used in the analyses have different reliability according to what was necessary to estimate for the inputs to evaluate the material data. For example, [6] has almost all material data necessary to perform the analyses and, in consequence, the analysis results related to those tests are more precise and reliable.

REFERENCES

[1] EPRI-NP-6301-D, **Ductile fracture handbook - Vol. 1 - Circumferential through-wall cracks.** Palo Alto , CA, USA: EPRI, 1989.

[2] EPRI-NP-2431, **A procedure for the assessment of the integrity of nuclear pressure vessels and piping containing defects**. Palo Alto, CA, USA: EPRI, 1982.

[3] Ross, E., K.-H. Herter, P. Julish, G. Bartholomé & G. Senski, **Assessment of large scale pipe tests by fracture mechanics approximation procedures with regard to leak-before-break**. *Nuclear Engineering and Design* 112: 183-195, 1989.

[4] Robert L. Cloud & Associates, Inc., **A specialized course in leak-before-break (LBB) for piping and pressure vessels**. São Paulo, Brazil: RLCA, 1992.

[5] Bartholomé, G., W. Kastner, E. Klein & R. Wellein, **Ruling-out of fractures in pressure boundary pipings. Part 2. Application to the primary coolant piping. Reliability of reactor pressure components**: 237-254. Vienna:IAEA, 1983.

[6] NUREG 1061, **Evaluation of potential for pipe breaks, Vol.3**. Washington, DC: United States Nuclear Regulatory Commission, 1984.

[7] Kastner W., E. Röhrich, W. Schmidt &R. Steinbuch, **Critical crack sizes in ductile piping**. International Journal on Pressure Vessels & Piping 9: 197-219, 1981.

[8] Sturm, D., W. Stoppler, K. Hippelein, J. Schiedermaier & H. Zhu, **Experimental investigations on the strength and fracture behaviour of circumferentially cracked piping under internal pressure and outer bending loading**. Design and analysis of piping, pressure vessels and components: 73-81. New York: ASME, 1987.