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CRACK INSTABILITY ANALYSIS METHODS FOR LEAK-BEFORE-BREAK PROGRAM IN PIPING SYSTEMS

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ABSTRACT

The instability evaluation of cracks in piping systems is a step that is considered when a high-energy line is investigated in a leak-before-break (LBB) program. Different approaches have been used to assess stability of cracks: a) local flow stress (LFS); b) limit load (LL); c) elastic-plastic fracture mechanics (EPFM) as J-integral versus tearing modulus (J-T) analysis. The first two methods are used for high ductile materials, when it is assumed that remaining ligament of the cracked pipe section becomes fully plastic prior to crack extension. EPFM is considered for low ductile piping when the material reaches unstable ductile tearing prior to plastic collapse in the net section. In this paper the LFS, LL and EPFM J-T methodologies were applied to calculate failure loads in circumferential through-wall cracked pipes with different materials, geometries and loads. It presents a comparison among the results obtained from the above three formulations and also compares them with experimental data available in the literature.

NOMENCLATURE

a - crack half-length
c - J-resistance curve parameter
D_N - nominal pipe diameter
D_0 - outside pipe diameter
E - Young modulus
J - J-integral (material or applied)
J_{inst} - J-integral at crack instability
J_{Ic} - J-integral at crack initiation
k_a, k_b - membrane and bending stress magnification factors
M_L - limit moment
m - J-resistance curve parameter
n - Ramberg-Osgood coefficient
R - mean radius = $(D_0\text{-}t)/2$
t - pipe thickness
P_b - bending stress
P_m - membrane stress
S_{eff} - effective stress
S_f - flow stress
S_u - ultimate stress
S_y - yield stress
T - tearing modulus (material or applied)
α - Ramberg-Osgood coefficient
θ - crack half-angle
Δa - crack extension

EPFM - Elastic-Plastic Fracture Mechanics
EPRI - Electric Power Research Institute
LBB - Leak-Before-Break
LFS - Local Flow Stress
LL - Limit Load

INTRODUCTION

The instability evaluation of cracks in piping systems is a step that is considered when a high-energy line is investigated in a leak-before-break (LBB) program. There are different methodologies that can be followed to assess crack instability such as: a) local flow stress (LFS) (Roos et al., 1982); b) limit load (LL) (EPRI, 1989); c) elastic-plastic fracture mechanics (EPFM) estimation procedures such as J-integral versus tearing modulus (J-T).

The first two concepts were discussed by the authors in a paper presented in last PVP conference, held in Minneapolis

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(Mattar Neto et al., 1994). As pointed out before, LFS is a theory used by Siemens/KWU to conduct LBB evaluation in German nuclear power plants (Bartholomé et al, 1989); LL, in a format presented in the Standard Review Plan 3.6.3 (1987) in some cases has been applied in LBB programs in the United States.

The application of LFS or LL concepts is restricted to ductile piping (austenitic wrought and nonflux welds) when the material has high resistance to crack propagation. If the ductility is not so high (austenitic flux welds, ferritic materials) the material will reach the unstable tearing prior to the limit load. In this case, the applicability of elastic-plastic fracture mechanics approach is mandatory.

This paper performs an evaluation of cracked pipes using an engineering approach for EPFM concept. This formulation is based on the J-T analysis, as presented in the Ductile Fracture Handbook (EPRI, 1989). An in-house computer software is developed to conduct the assessment of crack stability. The results obtained using the LFS, LL and EPFM methodology are compared with experimental data available in literature.

LOCAL FLOW STRESS AND LIMIT LOAD CONCEPTS

According LFS or LL concepts a circumferential through-wall crack in a high ductile piping will fail by plastic collapse. In this case, the flawed structure can be evaluated on the basis of the material strength rather than fracture mechanics, being limit stress or moment calculated considering equilibrium equations at cracked section.

If the LFS approach as stated in Roos et al. (1989) is considered, the failure is assumed to occur when the effective stress S_{eff} at one single point reaches flow stress. In this case:

$$S_{eff} = k_a P_m + k_b P_b \le S_f \tag{1}$$

where P_m is the membrane stress due axial loads (pressure plus external loads), P_b is the bending stress due external moment and S_f is the material flow stress (usually assumed as the average value of yield S_y and ultimate stress S_u). k_a and k_b are the membrane and bending stress magnification factors defined as:

$$k_a = \frac{1-\left(\frac{\theta}{\pi}+\frac{\sin 2\theta}{2\pi}-\frac{2\sin\theta}{\pi}\right)}{\left(1-\frac{\theta}{\pi}\right)\left[1-\left(\frac{\theta}{\pi}+\frac{\sin 2\theta}{2\pi}\right)\right]-\frac{2\sin^2\theta}{\pi^2}} \tag{2a}$$

$$k_b = \frac{\frac{\sin\theta}{\pi}\left(1-\frac{\theta}{\pi}\right)}{\left(1-\frac{\theta}{\pi}\right)\left[1-\left(\frac{\theta}{\pi}+\frac{\sin 2\theta}{2\pi}\right)\right]-\frac{2\sin^2\theta}{\pi^2}} \tag{2b}$$

where θ is the crack opening half angle and t is the pipe thickness as shown in figure 1.

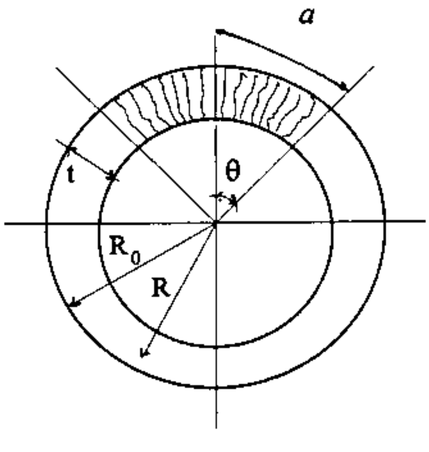


Figure 1. Cracked pipe geometry

According LL concept, as stated in EPRI (1989), for the global instability of the circumferential through-wall crack it is assumed that the net section of pipe has completely yielded. In order to predict the failure, the limit moment M_L is obtained using the equation:

$$M_L = 4S_f R_0^2 t\left(1-\zeta+\frac{\zeta^2}{3}\right)(\cos\gamma - 0.5\sin\theta) \tag{3}$$

where:

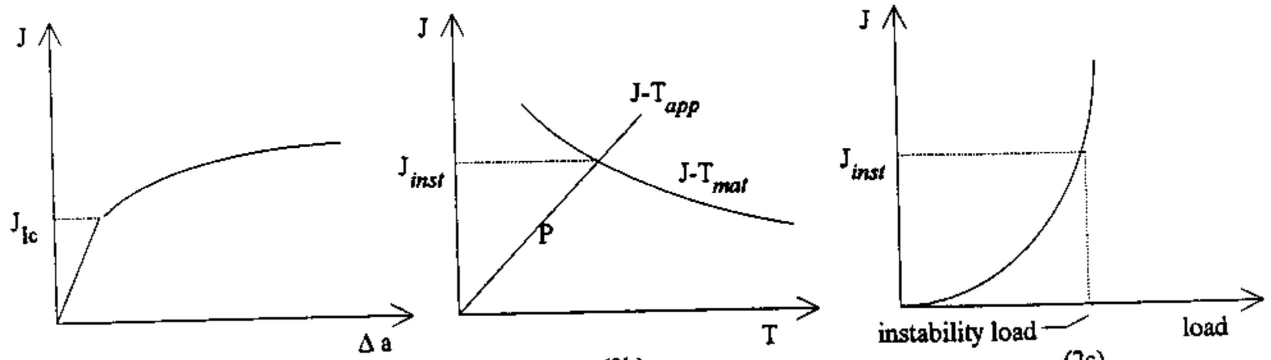
$$\zeta = \frac{t}{R_0} \tag{3a}$$

$$\gamma = \frac{0.5\theta(1-\zeta)\left(\frac{1+0.5\zeta}{1-\zeta}\right)}{(1-0.5\zeta)} + \frac{P}{\left[4S_f R_0 t(1-\zeta)\right]} \tag{3b}$$

The pipe external radius R_0 is showed in figure 1, also.

ELASTIC-PLASTIC FRACTURE MECHANICS

The EPFM is based on the concept of J-integral, being this parameter J used 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 EPRI (1989). According this reference, from the J-resistance curve obtained from fracture specimens tests (relationship between J and crack extension Δa) is possible to compute the J-T curve for the material. The crack driving force in terms of applied parameter J and tearing modulus T is calculated for the initial crack length as a function of load. The intersection of this curve and the J-T one for the material gives the instability value of J, defined as J_{inst}. The value of J_{inst} in a plot of parameter J versus load gives the associated instability load.



(2a) (2b) (2c)

Figure 2 - Crack instability evaluation (J-T analysis procedure)

The J-T analysis procedure, represented in figure 2, can be detailed as following. From the J-resistance curve for the material showed in figure 2a, is possible to find a correlation between J_{mat} and Δa in the form:

$$J_{mat} = c\,\Delta a^{m} \tag{4}$$

where c and m are curve fit constants determined in an empirical way. From this figure it is possible to get the J-integral at the initiation of crack growth, J_{Ic}. The material tearing modulus as a function of Δa is defined as:

$$T_{mat} = \frac{dJ}{da}\frac{E}{S_f^2} \tag{5}$$

where E is the Young's modulus and S_f is the flow stress. The plot of J-T from material is showed in figure 2b.

The J-T curve for applied loads in a piping with through-wall crack is computed from parameter J expressed in the form:

$$J_{app}(a) = J_e(a) + J_p(a) \tag{6}$$

being $J_e(a)$ and $J_p(a)$ the integral-J in the elastic and plastic regimes, respectively, available in EPRI (1989). These values are functions of the loads (axial and/or moment), the crack dimension $(\theta = a/R)$, the pipe geometry (R/t), and the material properties of stress-strain curve (E, S_y, n, α). n and α are the Ramberg-Osgood parameters.

The applied tearing modulus T_{app} is evaluated with equation (5) and with dJ calculated from equation (6) 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 connecting the origin of J and T axes with the point P defined by (J_{app}, T_{app}). As illustrated in figure 2b, the parameter J, at instability of the crack, is identified as J_{inst}. This value may be obtained from the intersection of J-T curve, for the material, and the straight line representing the applied J-T.

The load at instability corresponding to J_{inst} is obtained from figure 2c, which is a plot of $J_{app}(a)$, computed from equation (6), as a function of normalized applied load.

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 this time, the results from the integrity tests are not 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 to obtain the material properties and parameters required to perform the analyses. The reason is that some data were not available in the test references.

The material data information source used was EPRI (1989), Robert L. Cloud & Associates, Inc. (1992), and Bartholomé et al. (1983). In order to define those properties and parameters, some recommendations of NUREG (1984) are followed. They are summarized as:

a.) range of stress-strain curve that must be fit 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 estimate of the material J-resistance curve;

c.) fracture toughness specimens having approximately the same thickness as the pipe wall and without sidegrooves 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.

The results from methodologies LFS, LL and J-T were compared with the available experimental data considering pipes with circumferential through-wall cracks under internal pressure, bending moment, and internal pressure plus bending moment. The comparison between analytical versus experimental initiation and instability loads is showed in table 1 (internal pressure), table 2 (bending moment) and table 3 (internal pressure plus bending moment).

CONCLUSIONS AND COMMENTS

All the methods used in this paper are "engineering approaches" based on fracture mechanics with assumptions related to crack shape, consistent geometry, crack behavior, loads and load combinations, material properties and parameters. In some cases there were good consistency between the analytical results and the experimental ones. In other cases the agreement was not so good. That similarity might be function of the adjustment of some parameters and hypotheses adopted.

In general, the results show that the analytical methods give initiation and instability loads smaller than the experimental results. There is a good agreement with analytical and experimental results where the material properties and parameters are defined in a more precise way. It is meaningful to emphasize that material data used in the analyses have different reliabilities according to what was necessary to estimate for each one. For example, NUREG (1984) has almost all material data necessary to perform the analyses and, in consequence, the analyses results related to those tests are more precise and reliable.

The experimental data tests should be used carefully. For example, the tests K1 and K3 of table 1 (from Kastner et al. (1981)) present equal experimental instability pressures for pipes with the same geometric and material characteristics, but the initial crack lengths are completely different.

The instability loads obtained from J-T and LL analyses are, in general, greater than those obtained from LFS methodology. Apart the difficulties in J-T analysis to define the material properties and parameters, this procedure enables more appropriate conditions to evaluate the behavior of piping systems. This happens because the method allows to follow the crack growth from the beginning up to the crack instability.

The LFS and LL methods, although simpler in terms of formulation and material properties input, ended up in agreement with experimental results for materials with high ductility. This was observed in Mattar Neto et al. (1994). But such methods may give instability loads values much greater than the experimental ones where they are not fully appropriate, mainly with materials with low ductility.

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Table 1. Analytical versus experimental results.
Through-wall circumferential pipes under internal pressure

Tests	K1	K2	K3	K4	K5	K6	K7
D_0 (in)	6.98	29.85	6.98	29.85	4.3	4.3	27.72
t (in)	0.429	0.323	0.429	0.327	0.327	0.315	1.496
Material	A106B	Carbon St	A106B	Carbon St	10CrMoNiNh	10CrMoNiNh	20MnMoNi55
Angle	34°	42°	68°	76°	156°	200°	190°
P_{Exp} (ksi)	12.79	1.91	12.79	1.78	3.63	1.99	3.15
$P_{J\text{-}T}$ / P_{Exp}	1.30	0.75	0.95	0.58	1.71	1.18	0.73
P_{LL} / P_{Exp}	1.40	1.32	1.09	1.09	1.43	1.20	0.96
P_{LFS} / P_{Exp}	1.25	1.42	0.85	1.30	0.85	0.66	0.88

Tests:
K1 to K7 from Kastner et al. (1981)

P_{Exp}: Maximum Experimental Pressure (failure of the pipe)
$P_{J\text{-}T}$: Instability Pressure from J-T analyses
P_{LL}: Instability Pressure from LL analyses
P_{LFS}: Instability Pressure from LFS analyses

Table 2. Analytical versus experimental results.
Through-wall circumferential pipes under bending moment

Tests	D1	D2	D3	S1	S2	S3	R1	N1	N2	N3
D_0 (in)	16	16	16	31.5	31.5	31.5	27.5	16	4.51	2.375
t (in)	1.6	1.6	1.6	1.85	1.85	1.85	1.858	1.0276	0.354	0.237
Material	SS316	SS316	SS316	20MnMo Ni55	20MnMo Ni55	20MnMo Ni55	bainitic st	SS304	SS304	SS304
Angle	120°	40°	40°	60°	60°	20°	60°	132.3°	133.56°	133.56°
MExp Init (lbf in)	5.656E6	1.026E7	9.754E6	-	-	-	8.143E7	6.609E6	1.526E5	2.962E4
MExp Inst (lbf in)	6.665E6	1.250E7	1.191E7	8.541E7	7.877E7	1.231E8	8.541E7	6.957E7	1.576E5	2.996E4
MJ-T Init ÷ MExp Init	0.83	0.89	0.70	-	-	-	0.33	0.76	1.03	1.01
MJ-T Inst ÷ MExp Inst	0.75	0.78	0.63	0.82	0.89	0.81	0.39	0.81	1.05	1.00
MLL Inst ÷ MExp Inst	0.75	0.70	0.76	0.69	0.75	0.90	0.52	0.79	0.83	0.71
MLFSInst ÷ MExp Inst	0.76	0.44	0.44	0.39	0.42	0.59	0.29	0.48	0.52	0.45

Tests:
D1 to D3 from Le Dellion and Crouzet (1990)
S1 to S3 from Sturm et al. (1987)
R1 from Roos et al. (1989)
N1 to N3 from NUREG (1984)

MExp Init: Experimental initiation moment
MExp Inst: Experimental maximum moment (failure of the pipe)
MJ-T Init: Initiation moment from J-T analysis
MJ-T Inst: Instability moment from J-T analysis
MLL Inst: Instability moment from LL analysis
MLFS Inst: Instability moment from LFS analysis

Table 3: Analytical versus experimental results.
Through-wall circumferential pipes under internal pressure plus bending moment

Tests	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	76°	135°	60°	90°	45°	60°	60°
Internal Pressure (psi)	2,495	1,049	2,175	1,160	1,160	1,160	2,175
MExp Init (lbf in)	-	-	-	3.717E6	7.966E6	3.664E6	-
MExp Inst (lbf in)	1.221E5	8.348E4	4.868E7	7.028E6	1.133E7	4.903E6	4.868E7
MJ-T Init ÷ MExp Init	-	-	-	0.59	1.11	0.59	-
MJ-T Inst ÷ MExp Inst	0.88	0.80	0.43	0.34	0.79	0.47	0.57
MLL Inst ÷ MExp Inst	1.18	0.77	1.15	0.44	0.75	0.82	0.87
MLFS Inst ÷ MExp Inst	0.79	0.85	0.34	0.24	0.35	0.24	0.29

Tests:
K8 and K9 from Kastner et al. (1981)
S4 from Sturm et al. (1987)
R2 to R5 from Roos et al. (1989)

MExp Init: Experimental initiation moment
MExp Inst: Experimental maximum moment (failure of the pipe)
MJ-T Init: Initiation moment from J-T analysis
MJ-T Inst: Instability moment from J-T analysis
MLL Inst: Instability moment from LL analysis
MLFS Inst: Instability moment from LFS analysis