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INSTABILITY EVALUATION IN AUSTENITIC PIPING SYSTEMS USING TWO DIFFERENT APPROACHES

Miguel Mattar Neto
CNEN – SP/IPEN/COPESP
São Paulo, Brazil

Carlos T. E. DeAquino, José E. Maneschy, and Petrus G. B. Nóbrega
COPESP
São Paulo, Brazil

ABSTRACT

Instability evaluation, like Leak-Before-Break (LBB) concept, is an approach commonly used to verify the integrity of piping in nuclear power plants all over the world. If the material has enough ductility, the instability evaluation can be performed using either Local Flow Stress concept (LFS) or Modified Limit Load method (MLL). LFS is a theory used by Siemens/KWU to conduct LBB in German nuclear power plants. On the other hand, the MLL approach, as described in Standard Review Plan (SRP) 3.6.3, has been used to evaluate LBB in plants in the United States.

This paper presents a comparison between the results obtained by the above two formulations. Discrepancies will be pointed out in a critical way, showing the advantages and disadvantages in using each of the two different approaches.

NOMENCLATURE

a - full crack length
D_N - nominal pipe diameter
D_o - outside pipe diameter
k_a, k_b - membrane and bending stress magnification factors
M - load combination parameter
P_m, σ_a - membrane stress
R - mean radius = $(D_o\text{-}t)/2$
S - stress in flawed pipe
SI - stress index
t - pipe thickness
β - stress inversion angle
θ - half-angle of through-wall flaw
σ_b - bending stress
σ_f - flow stress
σ_u - ultimate stress
σ_y - yield stress
LBB - Leak-Before-Break
LFS - local flow stress
MLL - modified limit load
EPRI - Electric Power Research Institute
SRP - Standard Review Plan

INTRODUCTION

Leak-before-break (LBB) criteria can be used to eliminate postulated double-ended guillotine break in nuclear power plants. When LBB is applied successfully, the pipe whip restraints can be avoided in the design of high-energy lines. The removal or non-installation of such supports is very important because, besides minimizing construction and maintenance costs of the plant, it can reduce the level of radiation exposure for working personnel.

The crack instability assessment in piping systems, which is part of the LBB approach, can be done through various methodologies, such as, elastic-plastic fracture mechanics (EPFM), local flow stress concept, and modified limit load approach.

The EPFM is based on two methods: the deformation plasticity failure assessment diagram (DPFAD) and J-T analysis. In order to use it, two main problems have to be faced. First, the formulation is not simple. Second, it is necessary to know fracture properties of the materials at operating temperature (280°C) that most likely have to be obtained by testing or from industry material data bases.

If the material has a high ductility, local flow stress and modified limit load are methods possible to apply. In this case, besides the fact that theory involved is simpler than EPFM, instability characterization is based only on tensile tests properties, available in ASME Section III (1992).

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In this study it is assumed that material has enough ductility to allow the application of the two above mentioned simplified methods. Instability evaluations on flawed pipe to estimate load carrying capacity will be conducted through: a) local flow stress concept, approach commonly used by Siemens/KWU in designing nuclear power plants in Germany, (Roos et al., 1989) and; b) modified limit load concept, as described in Standard Review Plan 3.6.3 (1987), mainly used in plants built in the United States.

The main goal of this paper is to show how these two methods can be used to obtain critical crack lengths in pipes from information contained in piping stress analysis report. A short description of the main aspects of the concepts will be presented. Some examples related to the typical high-energy lines are used to illustrate the procedures. The results are compared with those from pipe fracture experiments that are available in NUREG 1061 (1984).

LOCAL FLOW STRESS CONCEPT

The Local Flow Stress (LFS) method, as stated in Roos et al. (1989), predicts unstable growth for through-wall circumferentially-oriented cracks in piping when the effective stress at one single point resulting from external loading reaches the flow stress,

$$\sigma_{\mathrm{eff}} = k_a\,\sigma_a + k_b\,\sigma_b \le \sigma_f \qquad (1)$$

where σ_{eff} is the effective stress at point B of Figure 1, k_a and k_b are the membrane and bending stress magnification factors, σ_a is the membrane stress due to axial loads and σ_b is the bending stress due to external moment. The flow stress σ_f is usually defined as the average value of yield (σ_y) and ultimate strength (σ_u) of the material. They can be obtained from conventional tensile tests at operating temperature of the piping system.

In deriving Equation (1), it should be noticed that the existence of a crack moves the section neutral axis, therefore, causing an additional contribution to the bending stress due to axial loading. For thin-wall cylinders, k_a and k_b can be defined as follows (Roos et al., 1989):

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

$$k_b = \frac{\dfrac{\sin\theta}{\pi}+\left(1-\dfrac{\theta}{\pi}\right)\cos\theta}{\left(1-\dfrac{\theta}{\pi}\right)\left[1-\left(\dfrac{\theta}{\pi}+\dfrac{\sin 2\theta}{2\pi}\right)\right]-\dfrac{2\sin^2\theta}{\pi^2}} \qquad (3)$$

where θ is the crack opening half angle, in radians, as shown in Figure 1.

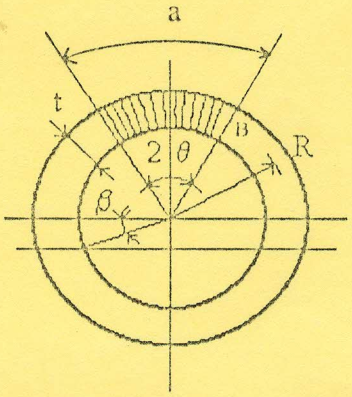

Figure 1 - Flawed Pipe Geometry

MODIFIED LIMIT LOAD

The Modified Limit Load (MLL) approach for studying failure mechanism in through-wall circumferentially-oriented crack in piping starts with the assumption of formation of a crack tip plastic zone. External loading produces an increase in plastic zone size up to the point that a plastic hinge forms at the piping cross section. According to this formulation, the unstable crack growth occurs when the acting stress becomes equal to the flow stress.

A procedure to predict the failure in piping can be found in SRP 3.6.3 (1987). Following the definitions of that document, a so-called master curve can be obtained from a stress index SI, given by

$$SI = S + MP_m \qquad (4)$$

plotted against the full crack length a=2θR where R is the mean pipe radius indicated in Figure 1. Membrane stress P_m accounts for axial loading. The M parameter is a margin on load combination, being 1.4 for algebraic and 1.0 for absolute combination. Bending stress S can be defined as follows:

$$S = 2\sigma_f\left(2\sin\beta-\sin\theta\right)/\pi,\quad \theta+\beta\le\pi \qquad (5)$$

in which

$$\beta = 0.5\left[(\pi - \theta) - \pi\left(P_m / \sigma_f\right)\right], \quad \theta + \beta \leq \pi \qquad (6)$$

As can be observed in Equations (5) and (6), the bending stress S takes into account only the contribution of the external axial loads and results from the asymmetrical disposition of the crack in the pipe section. Notice that there is no contribution from the external bending moment.

RESULTS

LFS and MLL formulation were employed to develop two in-house computer codes used to generate limit curves relating stress and crack lengths for circumferentially-oriented through-wall cracks. Figures 2 to 4 show results computed for austenitic steel piping under pure bending, whose geometric (D_N is the nominal pipe diameter, D_0 is the outside pipe diameter, t is the pipe thickness) and material properties are listed in Table 1.

D_N (in)	D_0 (mm)	t (mm)	σ_y (MPa)	σ_u (MPa)
2	60.3	6.0	251	603
4	114.5	8.9	266	622
16	406.4	26.1	316	640

Table 1 - Geometric and material properties (TP 304 steel)

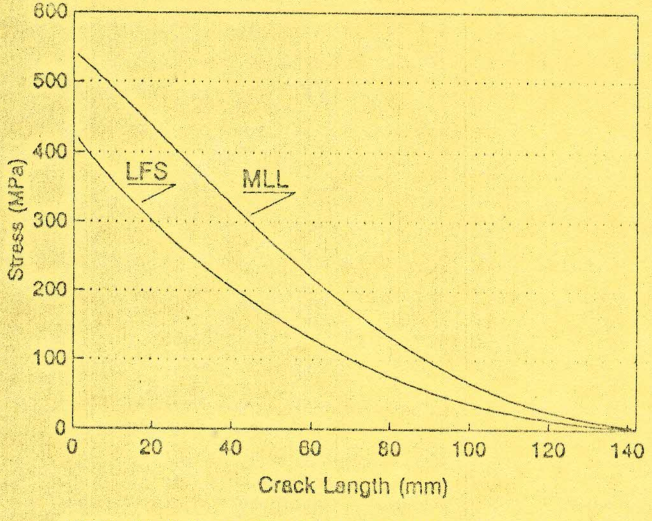

Fig.2 - Limit Curve for 2 in. Nominal Diameter Piping

According to NSAC-114 (1987), piping with nominal diameter less than 6 in. are not qualified for LBB application. However, the configurations listed in Table 1 were tested at EPRI and these examples could be used to compare analytical results with those determined experimentally.

These experimental results, included in NUREG 1061 (1984), provide the strength of flawed piping subjected to pure bending. The report presents critical crack lengths and bending moments that can cause failure. These moments are: 3.38 kNm, 17.34 kNm and 786.03 kNm for 2 in, 4 in and 16 in nominal pipe diameter, respectively.

In this paper, the geometries from Table 1 were used under the same loading condition as in NUREG 1061. Results based on LFS and MLL concepts, together with those achieved experimentally, are presented in Table 2.

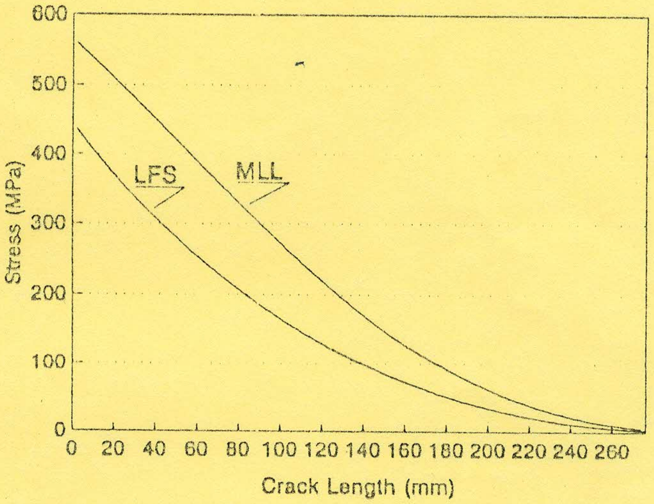

Fig.3 - Limit Curve for 4 in. Nominal Diameter Piping

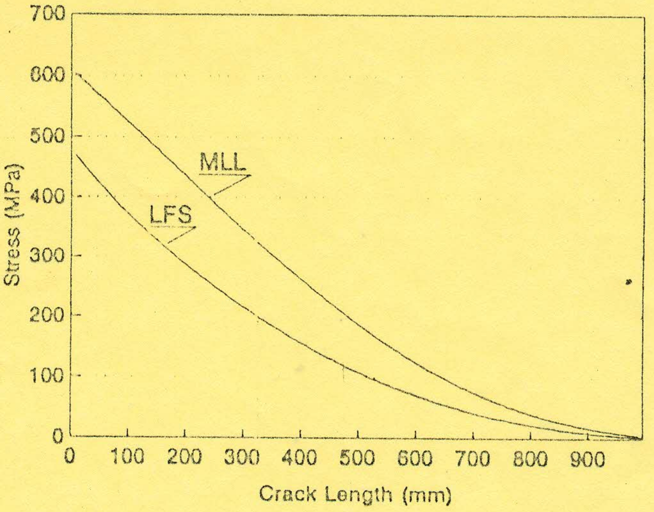

Fig.4 - Limit Curve for 16 in. Nominal Diameter Piping

D_N (in.)	NUREG 1061 (experimental)	LFS (analytical)	MLL (analytical)
2	63	26.2	50
4	122.7	66.7	113
16	442.3	205.5	375

Table 2 - Comparisons of critical crack lengths (mm) from experiments data and analytical procedures

The results shown in Figures 2 to 4 are consolidated in Table 2. This table shows critical crack lengths for the stress associated to the bending moments mentioned before. As can be seen, both formulations underpredict the critical crack length when compared to the experimental results. LFS formulation underestimates crack length more than MLL and this should be justified by two main reasons. Formerly, because in LFS concept it is assumed that failure occurs due to local yielding at a point of the cross-section, while, in MLL, the failure is preceded by general yielding of the pipe cross-section. Also, in generating limiting curves for MLL, as pointed out in the definition of S in Equations (5) and (6), no contribution due to external bending moment stresses are taken into account, while LFS considers such a contribution.

Similar results are presented in recent papers (Roos et al., 1989; Stadtmüller et al., 1992). These references show that critical crack lengths obtained from LFS methods are smaller than those from plastic limit load methods. Furthermore, the comparison shown in Bartholomé et al. (1989), Roos et al. (1989) and Bartholomé et al. (1993) indicate that LFS and plastic limit load methods provide failure stresses and critical crack lengths smaller than those obtained from experiments. From the work by Bartholomé et al. (1993), where the influence of different material properties, pipe dimensions and loading conditions was considered, it should be noticed that both LFS and plastic limit load methods are applicable to the assessment of instability in piping systems.

CONCLUSION AND COMMENTS

The paper examined two simplified methods to evaluate instability in piping with circumferential through-wall cracks. The main purpose of this calculation is to verify the applicability of these methodologies in the LBB concept.

Despite the small amount of experimental results available , the comparisons presented in this paper showed that MLL methodology seems to be more appropriate than LFS for austenitic steel pipes. This is due to the fact that, although MLL method still provides safe results, its conservatism is not as large as in LFS method.

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