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Critical circumferential through wall cracks in straight pipes under pressure and bending load regarding the relaxation by the local rotation of the flawed section

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Abstract:

The size of critical circumferential through wall cracks in piping systems depends much on the type of bending load (force or displacement controlled), the pipe has to carry. The method presented takes into account the unloading of the pipe due to the local rotation of the cracked section. More realistic critical crack sizes and, in consequence less uncertainty about the behaviour of welds with NDE indications are achieved by the application of this approach.

1. Introduction

Today most of the piping used in primary and secondary loops of nuclear power stations is manufactured without longitudinal welds. Thus the circumferential welds are a relevant item of the piping systems. Most of the non-destructive examination (NDE) is being performed here. To determine, if an indication found by non-destructive testing will end in a stable leak or in a rupture of the pipe, there exists a need to evaluate the critical crack size. A long series of theoretical and experimental work have been done in this area. The disadvantage of nearly all these approaches was, that there was no distinction between the force and displacement controlled loading. The bending moments, especially those by the thermal expansion of the hot system, (a typical displacement controlled moment), are looked at like force controlled moments. Thus, the relaxation of the piping system, due to the local rotation of the flawed section is not taken into account. The critical crack size generally is calculated by the nominal moment of the system. So critical crack sizes are very much smaller than the ones to be expected to cause pipe rupture. In this paper an analytical approach is presented, that handles the unloading by the local movement around the crack tip and in some axial distance of the crack, thus taking into account the relaxation of the load by the crack opening. The method is qualified by comparison with experimental and numerical results and is able to predict either realistic or conservative critical crack sizes in the range of interest. It is intended to use it for the safety analysis of piping systems in those cases, the load-controlled methods will predict unacceptably short critical crack sizes.

2. The technical problem of Leak-before-Break

The Leak-before-Break concept (LBB) in piping systems is one of the essential components of the principles of construction of technical piping systems. LBB states, that all NDE-indications found and not repaired will not yield to any leak due to the crack growth caused by the specified service loads. If there should be others than the expected loads, these indications will, in the worst case, result in a stable leak, but never in a pipe rupture. So the determination of the critical circumferential through wall crack length is one of the most important parts of LBB.

Fig. 1 shows the geometric and loading data, of the pipe considered, while Fig. 2 demonstrates the principle of LBB. The indication found by NDE is of size a_{NDE} x $2c_{NDE}$, , During the next service period it will grow due to the specified load cycles to a size limited by a_{PER} x $2c_{PER}$. Should there be any unexpected loads, they may cause the initial flaw to grow to a stable leak of length $2c_{LEAK}$ which is essentially smaller than the critical circumferential through wall crack of length $2c_{CRIT}$.

3. Loading of Piping Systems

The loading of piping systems may be divided into two classes:

- *force controlled loading*, caused by forces or moments, which will not be reduced by local relaxation of the system. Typical for this type of load are pressure and weight.
- *displacement controlled loading*, caused by movements of the system or enforced displacements. They may be reduced by local relaxation of the system. Typical for this type of load are thermal expansion and misfits during construction.

Stresses due to these loads are called primary or secondary stresses, the codes classify them and rule their handling in the stress analysis by different allowable stresses. This differentiation takes into account, that secondary loads may be reduced by local yielding of the ductile piping material. Table 1 summarizes the loading of a piping system, and indicates that locally, regarding one specific weld in a piping system, some of the loads classified as force controlled may be looked at as displacement controlled ones.

Loading	Classification (Codes)	local Class (wrt. weld)	Remark
pressure	force	force	no unloading
weight	force	displacement	may be supported in the system
earthquake	force	displacement	only small enforced displacements
thermal expansion	displacement	displacement	enforced displacements

Table 1: Classification of piping system loads

Weight and earthquake loading in most codes is handled as force controlled, but may be treated as displacement controlled, if it can be shown, that a local degradation of the system will result only in small local deflections, but not in essential displacements or rotations.

Fig. 3 indicates the mechanism: In an unflawed pipe, pipe end rotation γ_0 and bending moment M_0 are coupled by the laws of elasticity (Fig. 3a).

$$\gamma_0 \quad = M_o\, l / EI \qquad (1)$$

If the pipe section is nearly broken, only an ultimate fibre carries the axial load (Fig. 3c), the pipe end rotation γ_0 causes no bending moment, the weld is degenerated to a pinned joint. Between these two extremes, a pipe end rotation γ_0 in the case of a circumferential through wall crack of length $0 < 2\alpha < 2\pi$ will result in a bending moment smaller than the one of the unflawed pipe and a local rotation of the cracked region (Fig. 3b).

4. Methods to calculate critical circumferential through wall crack length $2c_{crit}$

Many research work has been performed to establish reliable methods to predict the critical circumferential through wall crack length $\mathbf{2c_{crit}}$ by numerous institutions [1]. Most of them may be integrated in four classes listed in Table 2. We subdivide these four approaches in the class of the first two ones, using flow stress σ_f ($R_p < \sigma_f < R_m$) as the only significant material property, while the last two ones use fracture mechanics properties (K_I, J, COD) as well.

Approach	Method	Material property
Flow stress concept	Load carrying capacity	flow stress σ_f
Plastic Limit Load	Load carrying capacity	flow stress σ_f
CEGB-Two Criteria Approach	Brittle-ductile fracture mechanics	$K_{I,}$ σ_f
GE-EPRI Approach	fracture mechanics	K_I, J, COD

Table 2: Accepted methods to calculate critical circumferential through wall crack length

The first two methods are easy to apply, as we need only yield stress R_p and ultimate stress R_m of the piping material to calculate the flow stress. So in most cases we will apply them, if we are not forced to use more sophisticated methods.

Common to all of these methods is to assume the bending load, calculated by the elastic stress analysis of the piping system, as a force controlled moment. Neither do they differentiate between primary and secondary loading, nor do they take into account the local unloading of the flawed section. So in all cases, there is an enforced pipe end displacement or rotation, these methods will predict critical crack sizes, which are essentially to small.

5. A new model to calculate critical circumferential through wall crack length

In 1981, Dippold et. al. [2] presented an idea, how this local relaxation may be integrated in a simple model, predicting a more realistic critical circumferential through wall crack length. The basic idea outlined in more detail in [1] may be found in Fig. 4 and Fig. 5. Ahead of the crack tip of the crack of half length α the plastic zone is shaped like a triangle in the angular region between α and β. (or an other representative shape of plastic zones like a circle). Up to an angle δ the stress distribution is an elastic one, from δ to π there is plastification due to compressive stress. Now at the border between the plastic and elastic region, the stress will be the flow stress, the axial strain

$$\varepsilon_f = \sigma_f / E \qquad (2)$$

and so the axial elongation of the plastic zone

$$\Delta l = \varepsilon_f \quad (\beta - \alpha)\, r \qquad (3)$$

is determined. This elongation Δl causes local rotation, as the neutral fibre at e1 will be of constant length.

$$\gamma_z = \Delta l / (r \cos \beta - e_1) \qquad (4)$$

The rotation found by this model can be interpreted as the main part of the rotation of a flawed section under bending load. For the case of combined pressure and bending load, the biaxiallity of the stresses must be looked at too, but the principles of the model are applicable as well.

6. Verification of the model

Fig. 6 compares the moment rotation curves of the method outlined above with FEM-results in the case of a PWR-feedwater pipe under pressure and bending load. Not only in this case but in all comparable piping systems, the moment rotation curves show good coincidence with numerical data. Especially the unloading, yielding to rotations greater than the ones calculated by eq. (1), is in good agreement. In addition to the curves the area between two curves is marked. This area corresponds to the energy released by the piping system, if the crack is elongated by the angle $\Delta\alpha = \alpha_i - \alpha_{i-1}$. Relating this energy to the new crack surface gives the J-integral as the energy release rate of the crack. Fig. 7 (see [1] for more details) compares the results predicted by our method with experimental and numerical data. In all cases we find our method to predict the critical circumferential through wall crack length in a realistic to conservative way.

7. Conclusions, Further Work

The method presented is able to help in the safety analysis of piping systems by evaluating circumferential through wall cracks in the case of displacement controlled bending moment, if Plastic limit load and Flow stress concept will predict very short cracks, due to their inability of handling the displacement controlled bending moment in an appropriate way. As most of the welds in piping systems connect pipes to bends, nozzles and T-joints, the method should be extended to these cases of welds as well.

Literature

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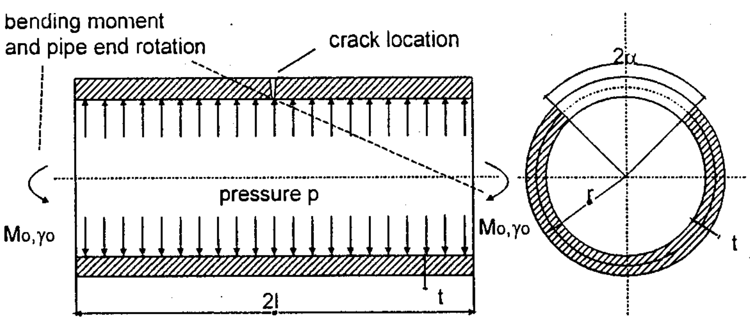


Fig. 1 Geometry and loading of a pipe containing a circumferential through wall cack

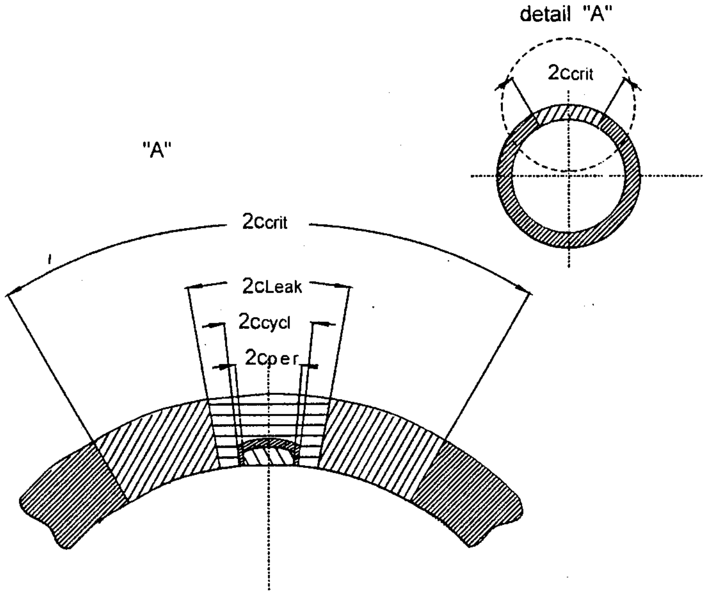


Fig. 2: Parameters of the leak-before-break-criterion

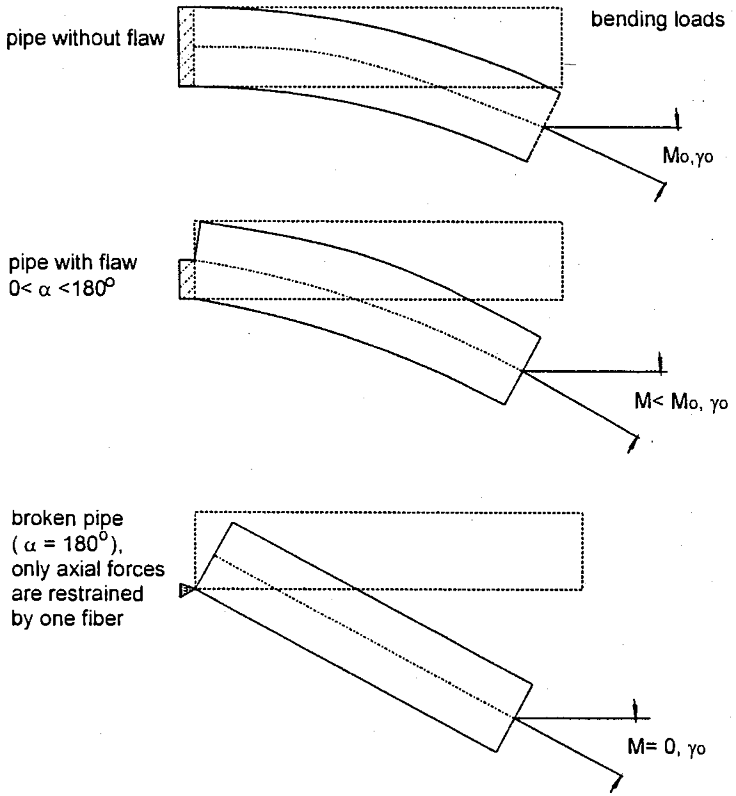
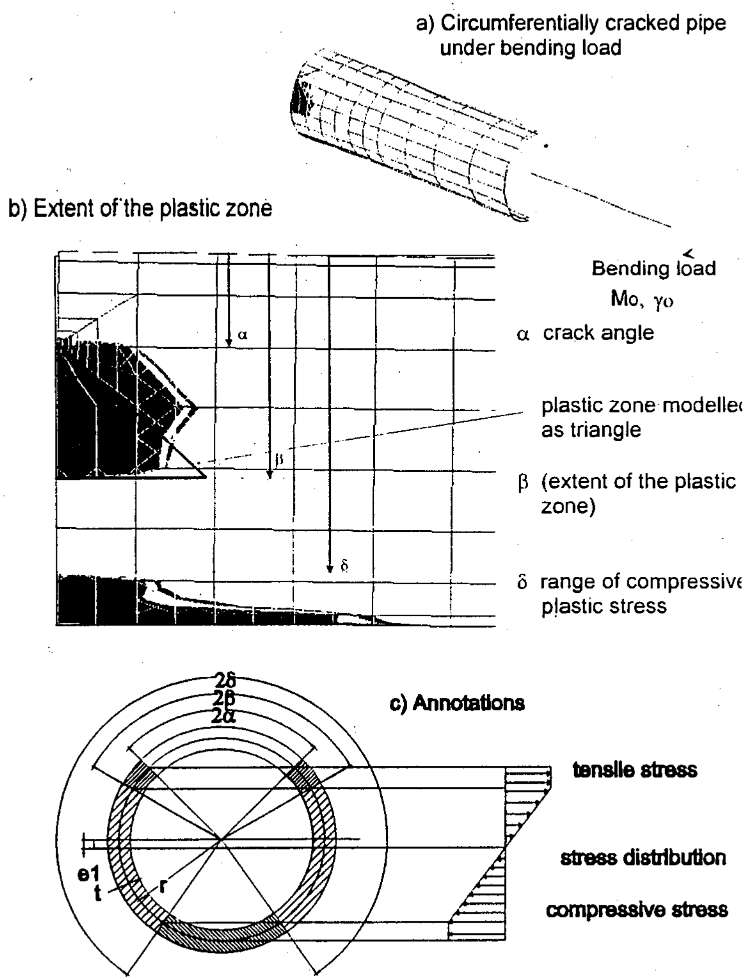


Fig. 3: Bending and rotation of flawed pipes


a) Circumferentially cracked pipe under bending load

b) Extent of the plastic zone

c) Annotations

Fig. 4: Stress distribution at circumferentially cracked pipes

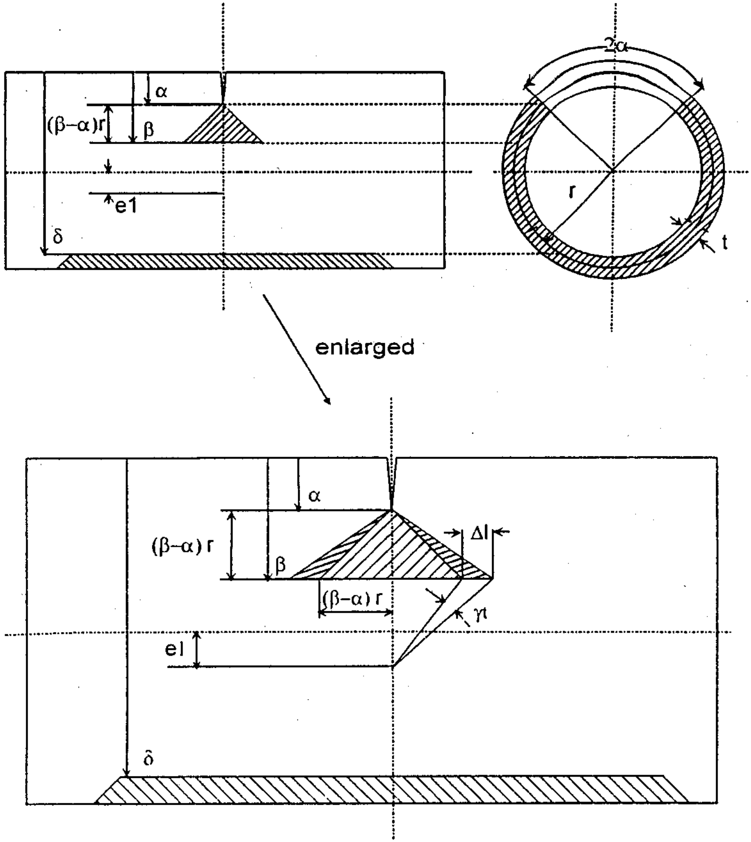


Fig. 5: Rotation of the plastic zone

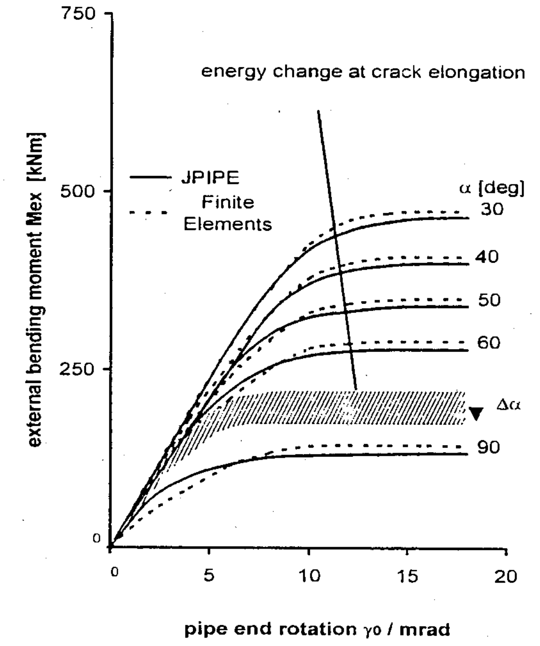


Fig. 6: comparison moment-rotation curves JPIPE-FEM

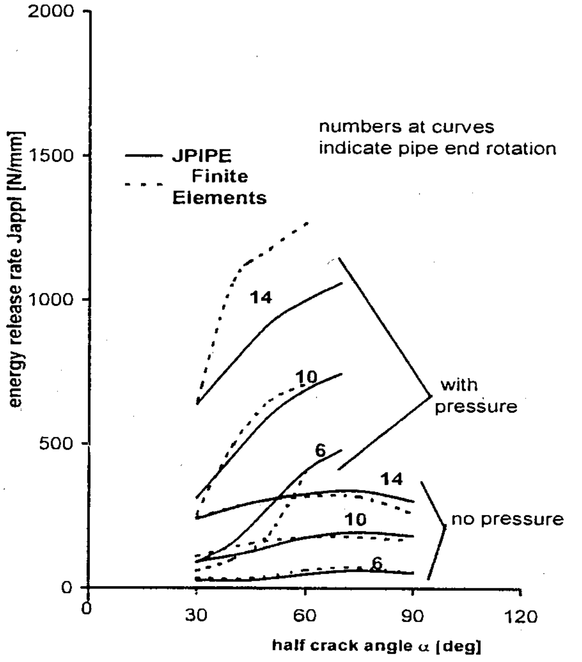


Fig. 7: comparison J-integral of JPIPE-FEM vs crack angle α