DUCTILE FAILURE OF PIPING

R. Steinbuch, G. Bartholomé
Kraftwerk Union AG, Erlangen,
Fed. Rep. of Germany

ABSTRACT

Methods are presented to deal with three questions of qualifying ductile piping. These are critical crack length, leakage areas and the dynamic behaviour of postulated cracks.

KEYWORDS

Critical crack size; leak before break, leakage areas, crack opening time.

INTRODUCTION

Though the microprocess of ductile failure of notched specimen is very difficult to describe, methods have been qualified to predict the overall behaviour of flawed components. These methods are commonly used in the evaluation of defects as well as for licensing procedures.

The first task is to determine critical crack sizes to exclude sudden failure of components with a certain flaw size. The second task is to develop a method for prediction of leakage areas to know the size of reaction and jet forces. The third task is to show how fast a postulated leak or break opens to the maximum area, as the hydrodynamic consequences depend on this time.

It is not possible to perform detailed finite element analyses of every occuring problem, so simple but qualified physical models have to be used. These models must reproduce experimental and finite element results.

CRITICAL CRACK SIZES IN PIPES

The formulation for axially through-wall flawed straight pipes is due to Eiber (1969)

$$\sigma^* = M_T \cdot \sigma_N = \sqrt{1 + 1{,}61 \frac{c^2}{r_m t}} \; \sigma_N \tag{1}$$

which is accepted as a lower bound curve for the prediction of critical through-wall flaws. For pipe bends, this formula modifies to (Kastner, 1980)

$$M_{Te}^{2} = 0{,}736 + 1{,}285 \frac{c^2}{r_m t} + 0{,}0276 \frac{c^4}{r_m^2 t^2} \quad \text{(extrados)} \tag{2}$$

$$M_{Ti} = 1{,}718 + 2{,}1369 \frac{c^2}{r_m t} - 0{,}05685 \frac{c^4}{r_m^2 t^2} \quad \text{(intrados)} \tag{3}$$

which gives a realistic prediction of experimental results (Fig. 1).

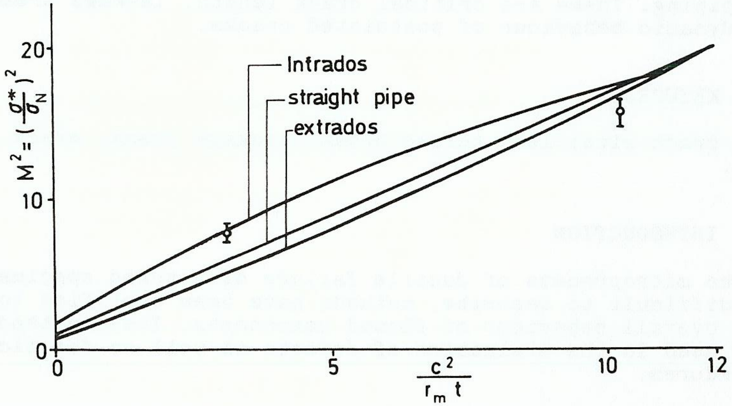

Fig. 1. Stress magnification factors for pipe bends.

For part-through wall flaws the critical stress can be calculated by (Eiber 1969):

$$\sigma^* = M_P \, \sigma_N = \frac{(1 - a/t \;\; M_T)}{(1 - a/t)} \, \sigma_N \tag{4}$$

Eq. (4) is used in combination with eq. (1) (resp. eq (2) or (3)) for the evaluation of discontinuities in welds (Fig. 2).

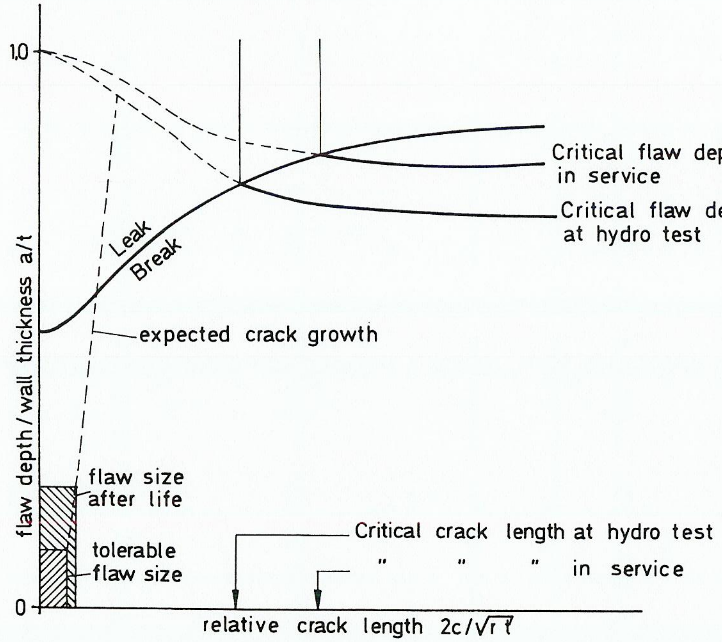

Fig. 2. The leak before break diagram.

First the critical crack length is calculated for all loading conditions, e. g. service and hydrotest. Then the critical crack depth for various pressures and increasing crack length is determined by eq. (4).

Finally one has to show that the flaw to be evaluated does not grow to the critical crack depth by the specified load cycles, but if it should grow faster, always remains shorter than the critical length (leak before break).

In the case of circumferentially flawed pipes the situation is more difficult as the load is not only internal pressure but also external bending moment caused by thermal expansion, weight and earthquake. For the critical through wall flaw the formulation

$$\sigma^* = \frac{\pi}{\pi - \alpha} \sigma_{ax} + \frac{\pi \, p \, r_i \, r_m^2 \frac{\sin\alpha}{\pi - \alpha} + M_{ex}}{(\pi - \alpha - 2 \frac{\sin\alpha}{\pi - \alpha} - \frac{1}{2} \sin 2\alpha) \, r_m^2 \, t} \tag{5}$$

with some modification is derived by equilibrium of momentum.

This approach gives non-conservative results in the case of part through wall flaws, so we propose another model. The bending moment by the eccentricity of the flawed cross-section acts not only in the plane of the flaw but in some axial distance too. There it causes a bending stress which, together with the stress by the external moment is augmented by the ratio f of ligament and wall thickness so

$$\sigma^* = \left(\frac{\pi}{\pi - f\alpha} + \frac{2f}{1-f} \; \frac{\sin\alpha}{\pi - f\alpha} \right) \frac{p\, r_i}{2\,t} + \frac{1}{1-f} \; \frac{M_{ex}}{\pi\, r_m^2\, t} \qquad (6)$$

which is a better description of the experimental results by Eiber (1971) (Fig. 3).

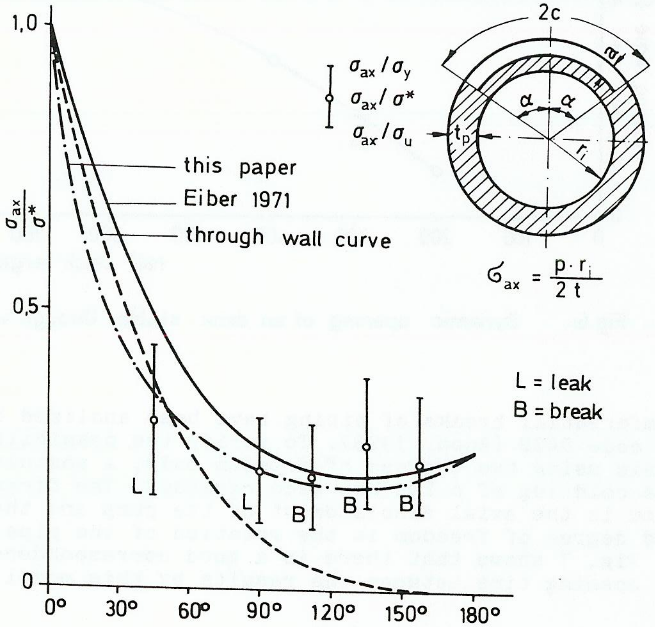

Fig. 3. Critical stresses for part-through wall flaws.

LEAKAGE AREAS

The displacement of the crack borders can be estimated by a rough extrapolation of Sneddons equation

$$V(x) = \frac{4 K_I}{E} \sqrt{\frac{X}{2\pi}} \qquad (7)$$

and then

$$A = \frac{32}{3} \; \frac{K_I}{E\sqrt{2\pi}} \left[(c + r_{pl})^{3/2} - r_{pl}^{3/2} \right] \qquad (8)$$

where the length of the plastic zone is added to the crack. This area is multiplied by factors (Erdogan 1972) for axially and circumferentially flawed pipes. This area is a good estimate for short cracks (compared to the critical crack length), but it predicts too small leaks for critical cracks. Fig. 4 shows this method compared to some finite element results on circumferential flaws.

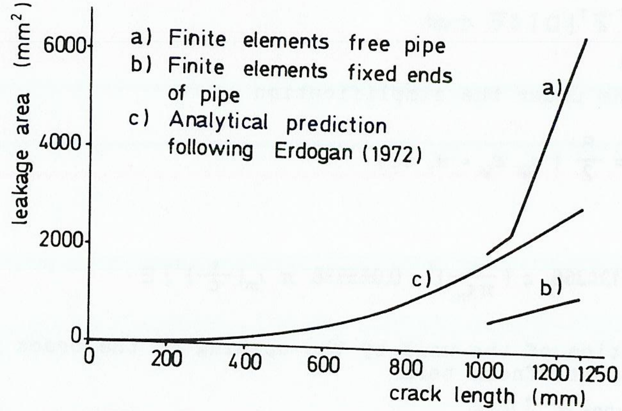

Fig. 4. Leakage areas of circumferentially flawed pipes.

DYNAMIC BEHAVIOUR OF CRACKS

The dynamic opening of a axially cracked pipe has been calculated by Ayres (1972) using finite elements. With a one-element model a good agreement can be achieved:

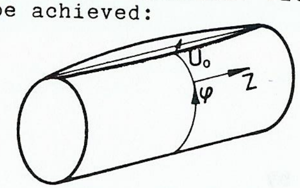

Fig. 5. Coordinates of the dynamic opening pipe.

The cracked pipe length is assumed to have a displacement (Fig. 5)

$$u(\varphi, z) = u_o \left(2\frac{\varphi^2}{\pi^2} - \frac{4}{3}\frac{\varphi^3}{\pi^3} + \frac{1}{3}\frac{\varphi^4}{\pi^4} \right) \left(1 - \frac{6}{5} z^2 + \frac{1}{5} z^4 \right) \qquad (9)$$

where u is the radial movement of any point (φ, z) on the pipe, u_o the displacement of the point in the midth of the crack. The bending strains result in

$$\varepsilon_\varphi = \frac{\partial^2 u}{r^2 \partial \varphi^2}$$

$$\varepsilon_z = \frac{\partial^2 u}{\partial z^2} \qquad (10)$$

$$\gamma_{\varphi_z} = \frac{\partial^2 u}{r \partial \varphi \partial z}$$

These strains are used to derive the stiffness by

$$\delta W_K = \int_{vol} \vec{\varepsilon}^{\,T} [D] \, \delta \vec{\varepsilon} \; d\,vol \qquad (11)$$

which yields under the simplification

$$\frac{\partial W_K}{\partial Vol} = \frac{E}{2} \left(\sigma_\varphi \varepsilon_\varphi + \sigma_z \varepsilon_z \right) \qquad (12)$$

$$K = \left[0{,}134366 \; c \left(\frac{t}{\pi r_m} \right)^3 + 0{,}065738 \; \pi \; r_m \left(\frac{t}{c} \right)^3 \right] E \qquad (13)$$

The elongation of the wall by the opening of the crack results in a second stiffness term

$$K_L = 0{,}1881 \; E \; \frac{t \pi r_m}{c^3} \qquad (14)$$

which gives a force

$$F_L = K_L \cdot u_o^3 \qquad (15)$$

The mass is derived by

$$\delta W_M = \int_{Vol} \varrho \, \ddot{u} \, \delta u \; d\,vol \qquad (16)$$

to

$$M = 0{,}1294 \; \varrho \; t \; \pi \; r_m \; c \qquad (17)$$

and the external force by

$$\delta W_{ex} = \int_{A_i} p \, \delta u \; dA_i' \qquad (18)$$

to

$$F_{ex} = 0{,}256 \; p \; \pi \; r_i \; c \qquad (19)$$

As we do not include damping effects the differential equation to integrate is

$$M \ddot{u}_o + K u_o + K_L u_o^3 = F_{ex} \qquad (20)$$

The time up to the maximum opening of a crack is shown in Fig. 6 compared with results analogous to that by Ayres (1977). As this method is realistic it can be used to calculate the opening time of stable through-wall cracks.

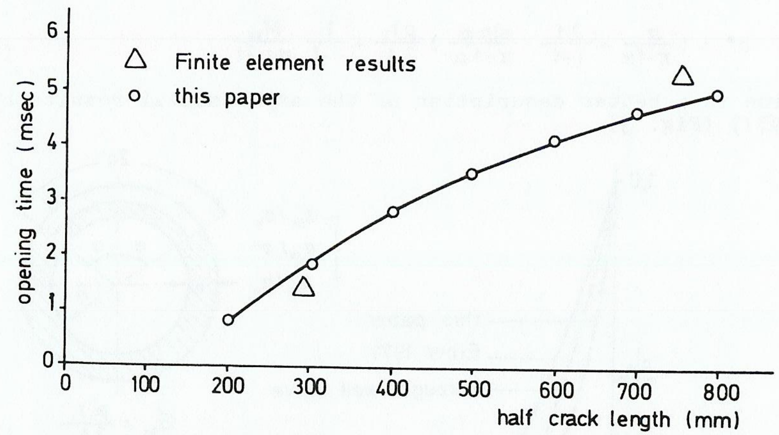

Fig. 6. Dynamic opening of an axial stable through wall crack.

Circumferential breaks of piping have been analized by the computer code DAGS (Anon. 1975). To verify the possibility of an analysis using two degrees of freedom only, a postulated break of the cold leg of a PWR has been regarded. The first degree of freedom is the axial displacement of the pump and the pipe, the second degree of freedom is the rotation of the pipe around the pump. Fig. 7 shows that there is a good correspondence of the break opening time between the results by this model and DAGS.

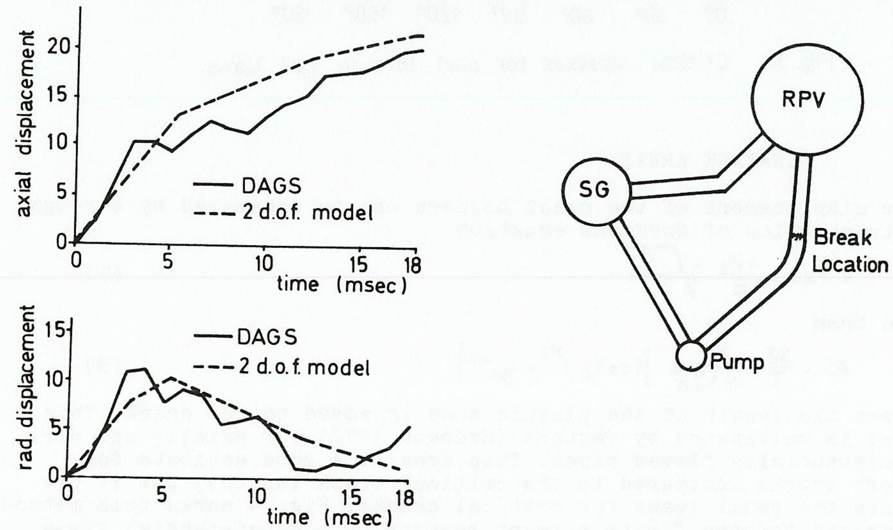

Fig. 7. Displacement of the broken cold leg.

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