EVALUATION OF DEFECTS IN WELDS FOR BRITTLE AND DUCTILE FAILURE MODES

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ABSTRACT

The question whether a defect in welds has to be repaired or not is analized for brittle and ductile failure modes. A method for the calculation of critical dimensions of axial and circumferential part-through-wall and through-wall cracks will be presented. The catastrophic failure of a component is excluded by a crack growth analysis.

KEYWORDS

Two criteria approach; leak-before-break; critical crack length and depth; straight pipe and pipe bends; crack growth;

INTRODUCTION

There is an increasing quality and extended application of non-destructive examination, so applicable fracture mechanics get more important. For power stations e. g. during the in-service inspection quick answers are necessary to the question, if a flaw is tolerable or not.

FAILURE MODES

The high standard in design and fabrication of power stations lead to the fact, that the failures to be expected are caused by small defects. These discontinuities may result in a leak or a break immediately or after some time. The modes of failure are governed by the material properties, the temperatures and the loads. We have to show that during the life of a component neither brittle nor ductile failure will occur.

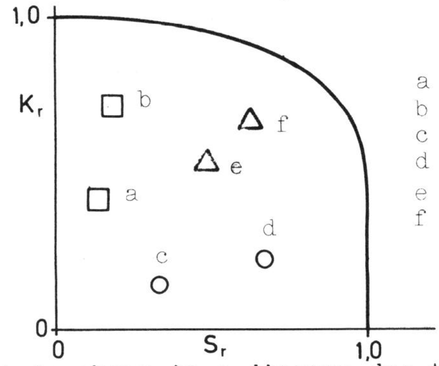

Fig. 1.
The failure assesment line

a	hydro-test	begin
b	"	end
c	service	begin
d	"	end
e	thermal shock	begin
f	"	end of life

In Fig. 1 a defect is shown in a diagram due to Harrisson (1977) under some loading conditions such as hydro-test, service and thermal shock at begin and end of life. You may not have to repair a defect if there is a sufficient distance between all positions of the defect (i. e. all loading conditions) in the diagram and the failure curve.

This failure curve is the connection between purely brittle material behaviour where the yield stress $\sigma_y \rightarrow \infty$ and the failure criterion is

$$K_I = K_{Ic} \tag{1}$$

and the purely plastic behaviour where $K_c \rightarrow \infty$ and failure occurs if the local stress reaches yield:

$$\sigma = \sigma_y \tag{2}$$

This approach is based on Dugdale´s work (1960) who showed that for increasing K_c the failure criterion changes as shown by

$$\frac{\sigma}{\sigma_y} = \frac{2}{\pi} \cos^{-1} \exp\left\{-\frac{\pi}{8}\frac{K_c^2}{\sigma_y^2 c}\right\} \tag{3}$$

The task is now to determine the stress intensity factor K_I, the stress σ in the uncracked ligament and the crack growth during life to decide if the defect has to be repaired.

DETERMINATION OF K_I (BRITTLE FRACTURE)

Very much literature exists on the determination of K_I-values in given geometries, so we only present a list of authors whose solutions we use in special problems:

a) two dimensional problems

surface flaw	Fig. 2	Tada (1973)
subsurface flaw	Fig. 3	Isida (1966)

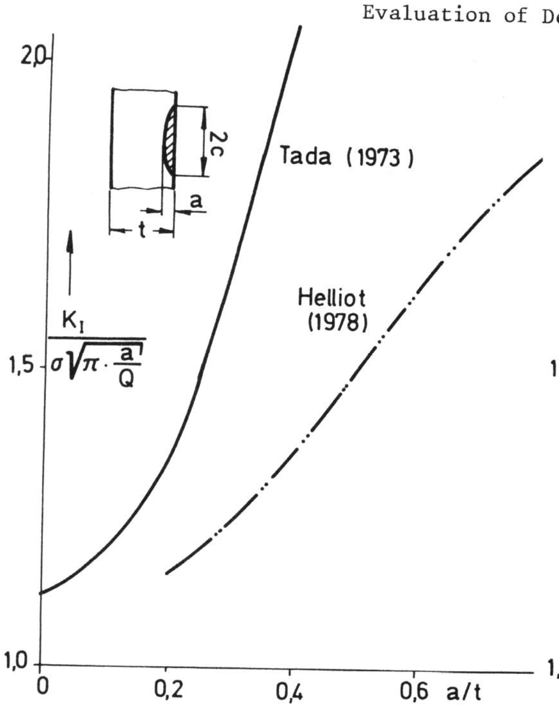

Fig. 2. K_I for surface flaws

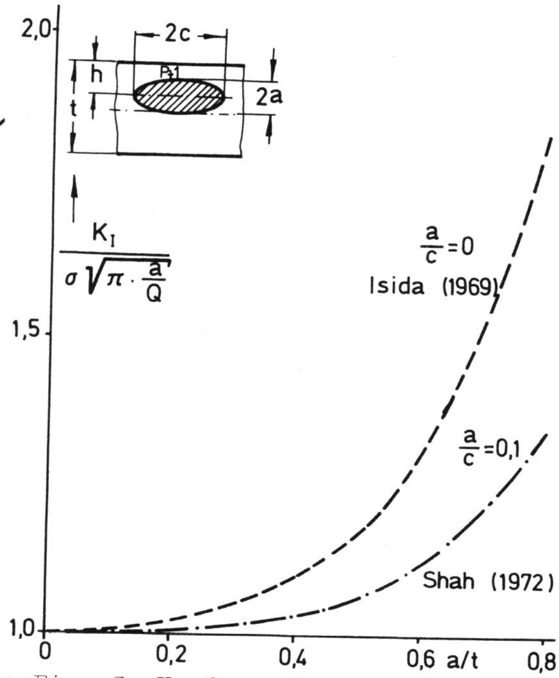

Fig. 3. K_I for subsurface flaws

b) three dimensional problems

surface flaw	Fig. 2	Helliot	(1978)
subsurface flaw	Fig. 3	Shah	(1972)

These solutions are the mostly agreed ones, even there are others, sometimes contradicting proposals (e.g. ASME-Code 1977).

DETERMINATION OF LOCAL STRESSES (DUCTILE FRACTURE)

As eq. (3) is valid only for large plates, for real structures the stress in the vicinity of the crack has to be computed by the stress of the unflawed structure and the geometry of the defect. In general one introduces the so-called stress magnification factor M and modifies eq. (2) to

$$\sigma_y = M\sigma \tag{4}$$

For real material σ_y should be replaced by the flow stress, which is somewhere between yield and ultimate stress and has to be determined experimentally.
For axially flawed straight pipes M is given by (Eiber 1969)

$$M = \sqrt{1 + 1,61\,\frac{c^2}{r_m\,t}} \tag{5}$$

which has been shown to be conservative. Sometimes the coefficient 1.61 is replaced by smaller values or higher order terms are introduced according to the original formulation by Folias (1969).

For axially flawed elbows with a ratio of bending radius to pipe radius of 3 we derived stress magnification factors of

$$M_e^2 = 0{,}736 + 1{,}285 \frac{c^2}{r_m t} + 0{,}0276 \frac{c^4}{r_m^2 t^2} \tag{6}$$

for the extrados and

$$M_i^2 = 1{,}718 + 2{,}13697 \frac{c^2}{r_m t} - 0{,}05685 \frac{c^4}{r_m^2 t^2} \tag{7}$$

for the intrados

These formulae result from a finite element analysis which is outlined in reports of KWU (Kastner, 1980a, 1980b). The idea was to do an analysis with the same mesh for a straight pipe and a pipe bend to investigate the differences of the stress ahead of the crack tip as well as the leakage areas.

Fig. 4 showes the meshes used in this analysis, including the one for circumferentially flawed pipes.

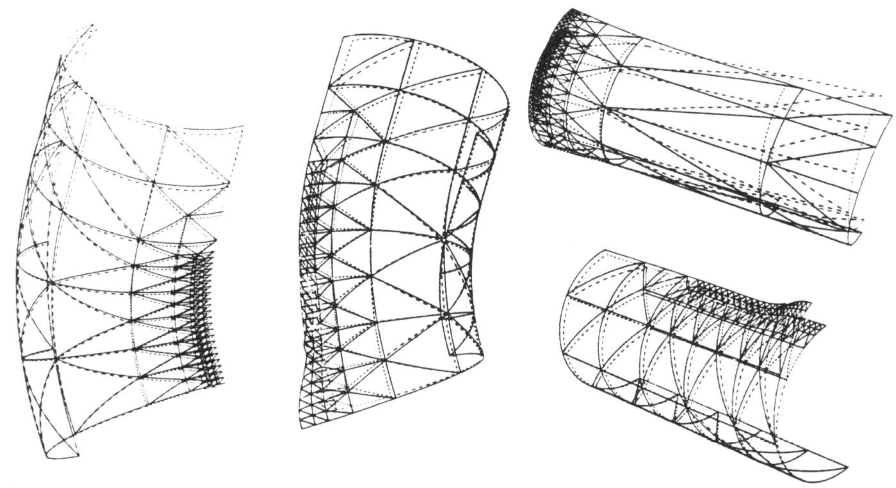

Fig. 4. Meshes for the finite element analysis

Eqs. (6) and (7) are shown in Fig. 5 together with eq. (5) and two experiments performed by KWU (Kastner, 1980a) and Westinghouse (Szyslowski, 1972). Care should be taken as eq. (6) and (7) are valid only if $c^2/r_m\ t \leq 12$.

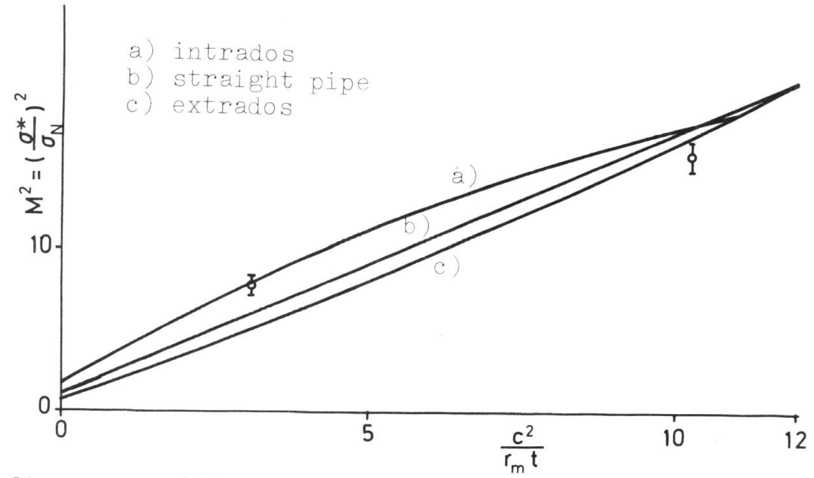

Fig. 5. Stress magnification factors for pipe bends

For part-through-wall crack one generally uses:

$$M_p = (1 - a/t\ M) / (1 - a/t) \tag{8}$$

which describes whether a flaw grows to a leak without regarding if this is a stable one or not. Fig. 6 demonstrates the meaning of eq. (8):

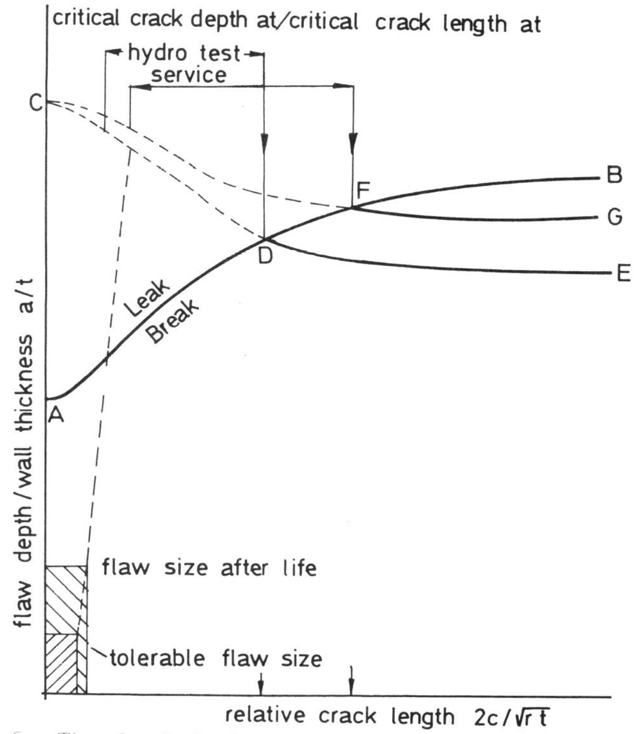

Fig. 6. The leak before break diagram

In case of a failure a defect causes a break if it is below the line AB, else a stable leak, but to fail, the stress level (curves CDE and CFG) must touch the defect, i. e. the stress level must be high. To show relations a defect which will be left after US-inspection is drawn together with the line of its expected growth. This defect will not reach the critical crack size by the expected load cycles, but if it should grow faster by any reasons it will cause a leak.

For circumferentially through-wall cracks the solution is given by equilibrium of momentum. The critical crack angle α can be calculated by

$$\sigma_y = \frac{\pi}{\pi-\alpha}\,\sigma_{ax} + \frac{\pi\, p\, r_i^2\, r_m \dfrac{\sin\alpha}{\pi-\alpha} + M_{ex}}{\left(\pi - \alpha - 2\dfrac{\sin\alpha}{\pi-\alpha} - \dfrac{1}{2}\sin 2\alpha\right) r_m^2\, t} \tag{9}$$

where the loading is internal pressure p and external bending momentum M_{ex}.

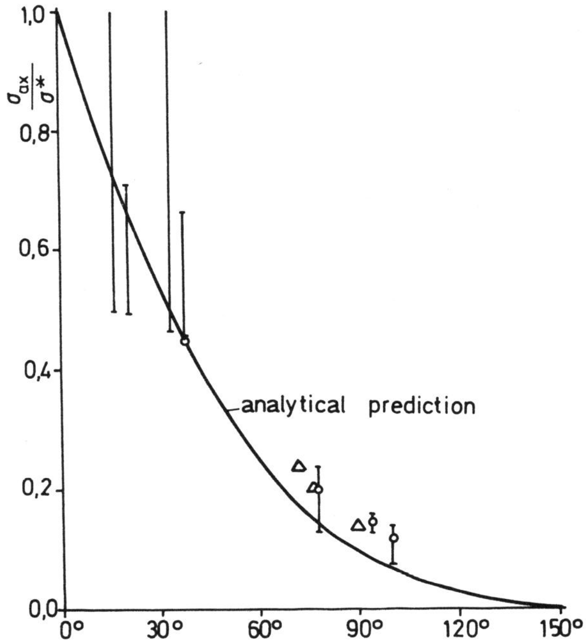

Fig. 7. Circumferential through wall cracks comparison of theory and experiments

Fig. 7 shows, that this approach is very conservative compared to some experiments (Kastner, 1980a, Zeibig (1973), Watanabe 1977) and finite element results, because it does not account for the biaxiality of stresses and the plastification of the material.

This approach has the disadvantage, that the external moment, which reduces by local yielding, enters eq. (9) as force. So for some piping systems failure is predicted, even if this system has a good ability to withstand flaws.

For part-through-wall circumferentially flawed pipes there exist similar approaches (Eiber 1971), but they do not describe conservatively experimental results.

The formulation we propose is based on the assumption, that the bending moment caused by the eccentricity of the flawed cross-section does not act only in the plane of the flaw but also in some distance in the pipe. The stress caused by it plus external momentum is increased by the ratio f of wall thickness t and ligament t-a. The critical stress can be calculated by

$$\sigma_y = \left(\frac{\pi}{\pi - f\alpha} + \frac{2f}{1-f}\,\frac{\sin\alpha}{\pi - f\alpha}\right)\frac{p\,r_i}{2t} + \frac{1}{1-f}\,\frac{M_{ex}}{\pi\,r_m^2 t} \qquad (10)$$

The stresses predicted by eq. (10) are compared with the formulation and some experiments from Eiber (1971) Fig. 8.

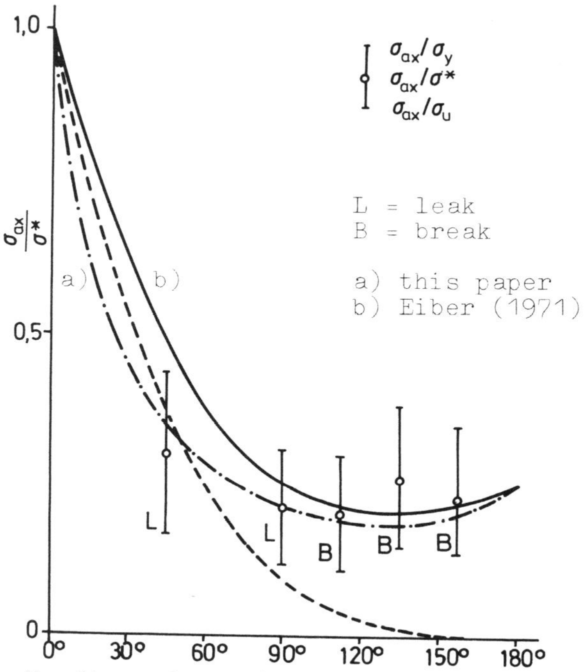

Fig. 8. Circumferential part through wall cracks comparison theory and experiments

CRACK GROWTH ANALYSIS

The application of crack growth analysis does not try to understand the microscopic processes but to correlate the macroscopic values Δa and ΔK as in Paris´ law:

$$\frac{da}{dN} = c_o\,(\Delta K)^n \tag{11}$$

or one of its modifications.

The material properties C_o and n depend very much on the environment, the stress ratio $R = \sigma_{min}/\sigma_{max}$, the frequency of the loading cycles, and the temperature.

A typical modification of Paris´ law is shown in Fig. 9, where the change of Δa with the variation of R at the same ΔK is indicated.

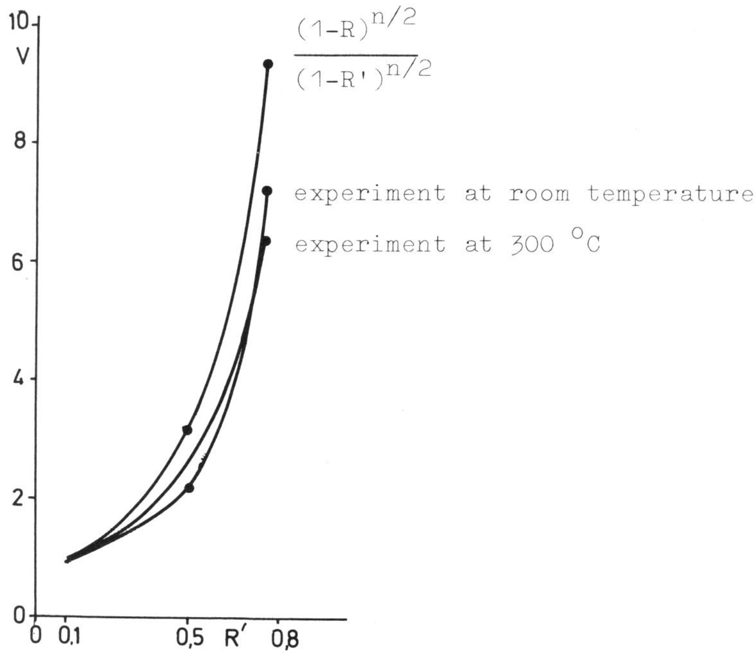

Fig. 9. Acceleration of crack growth with increasing R'

Eq. (11) modifies to

$$\frac{da}{dN} = c_o \cdot v \cdot (\Delta K)^n \tag{12}$$

where

$$V = \frac{(1-R)^{n/2}}{(1-R')^{n/2}} \tag{13}$$

and R is the stress ratio at the experiment, R′ the ratio under service conditions. Fig. 10 indicates that the outlined method is only valid if the level of ΔK is in the linear range of the log-log plot of the experimental data.

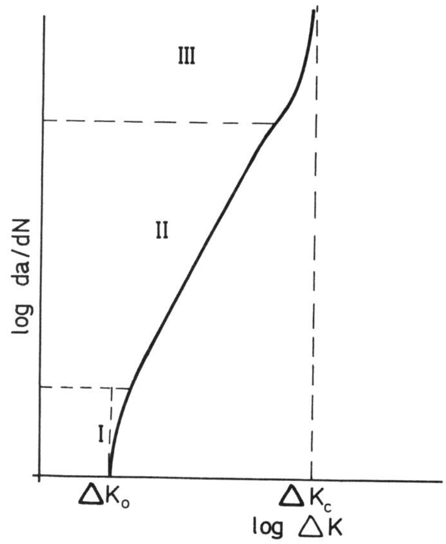

Fig. 10. The limits of Paris' law

FINAL REMARKS

It has been demonstrated that fracture mechanics can be used for quick practical applications.

The points we have to look at in the next future are stress intensity factors of three dimensional crack problems especially for deep flaws and the influence of local yielding to external momentum in the case of circumferentially flawed pipes.

Literature

ASME-Code (1977). Section XI, App. A, (1977).

Dugdale, D. S. (1960); Yielding of Steel Sheets Containing Slits. J. Mech. Phys. Solids, 8, 100 - 104, (1960).

Eiber, R. et al. (1969). Investigation on the Initiation and Extend of Ductile Pipe Rupture. BMI 1866 Battelle Columbus Laboratories, Columbus, Ohio (1969).

Eiber, R. et al. (1971). Investigation on the Initiation and Extend of Ductile Pipe Rupture. BMI 1908. Battelle Columbus Laboratories, Columbus, Ohio (1971).

Folias, E. S. (1969). On the Effect of Initial Curvature on Cracked Sheets. UTEC CE69-002 (1969).

Harrisson, R. P. et al. (1977). Assessment of the Integrity of Structures Containing Defects. C.E.G.B. Report R/H/R6 REV-1 (1977).

Helliot, J. et al. (1978). Semi Elliptical Cracks in a Cylinder Subjected to Stress Gradients. Lecture presented at the XIth National Symposium on Fracture Mechanics, Blacksburg, Virginia (1978).

Isida, M. (1966). J. Applied Mechanics, September 1966, 674 - 675 (1966).

Kastner, W. et al. (1980). Experimentelle Untersuchungen zum Versagen von Rohrleitungen, Vergleich mit theoretischen Vorhersagen. Lecture presented at the Annual Meeting Kerntechnik, Berlin (1980).

Kastner, W. et al. (1980). Critical Crack Sizes in Ductile Piping, to be published.

Shah, R. C. and Kobayashy, A. S. (1972). On the Surface Flaw Problem. The Surface Crack: Physical Problems and Computational Solution. Winter Annual Meeting of ASME (1972).

Szyslowski, J. J. et al. (1972). Determination of Design Pipe Breaks for the Westinghouse Reactor Coolant System. WC AP-7403, Rev. 1, (1972).

Tada, H. et al. (1973). The stress analysis of Cracks Handbook, Del Research Corporation, Hellertown, Pennsylvania (1973).

Watanabe, M. et al. (1977). Mechanical Behaviour on Bursting of Longitudinally and Circumferentially Notched AISI-304 Stainless Steel Pipes by Hydraulic and Explosion Tests. Third International Conference on Pressure Vessel Technology, Tokio (1977).

Zeibig, H., Fortmann, F. (1973). Fracture Behaviour of Ferritic and Austenitic Steel Pipes. 2. SMiRT, Paper F4/8, Berlin (1973).