Probabilistic Fatigue Crack Growth in a Pipe Elbow of a Fast Breeder Reactor

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Abstract

Probabilistic fracture mechanics is used to estimate the reliability of a pipe elbow of the German fast breeder reactor. Fatigue crack growth and plastic instability are considered to be the dominant failure mechanisms. For the calculations of the failure probabilities as a function of time, a new code called PARIS has been developed which is expected to be applicable to a wide variety of problems in probabilistic fracture mechanics.

Among the pipings used in the German fast breeder reactor the pipe elbow connected directly to the reactor tank is exposed to the highest stresses and therefore constitutes the most critical part. In a probabilistic analysis using the PARIS-code /1/, the failure probability of this pipe elbow resulting from stable and instable crack extension is calculated.

In the first section of this paper the input data are summarized. Additionally, a few characteristic features of the PARIS-code are described and compared with the PRAISE-code /2/. The second section deals with results obtained up to now for the pipe elbow, whereas in the last section an outlook to future investigations is given.

1. Statistical Model

The pipe elbow considered is made of austenitic stainless steel of the German designation 1.4948 similar to AISI 304 steel. Its geometry is shown in Fig. 1. Stresses under operational and emergency conditions arise mainly due to restrained thermal expansions of the piping system. For the elastic and elasto-plastic stress analysis see chapter 6.1 in reference /3/. In this paper, only the weld A-B is considered. The variation of the equivalent plastic stress along the circumference of the pipe is given in Fig. 2. To take into account the scatter of stress due to geometrical inaccuracies in the pipe elbow (e.g. variation of wall thickness, mismatch of the parts) and due to fluctuations in external load, a normal distribution was assumed with a mean value equal to the equivalent plastic stress and a coefficient of variation of 10%.

The fatigue data at operating temperature provided by INTERATOM /4/ were analysed with the crack growth law of Walker /5/

$$\frac{da}{dN} = C\left(\frac{\Delta K}{(1-R)^m}\right)^n, \quad m = 0.6, \; n = 4.08 \qquad (1)$$

where the coefficient C was taken to be a lognormal distributed variable with the mean value $8.32 \cdot 10^{-14}$ (ΔK in $\frac{N}{mm^{3/2}}$, a in mm) and the standard deviation $8.31 \cdot 10^{-14}$ in order to take into account the scatter in crack growth data. As it was realized during the experimental evaluation /6/ that the data can be described with satisfactory accuracy by a da/dN-ΔK relation no attempt was made to use an elastoplastic crack growth law. With this result in mind it was felt that the stress amplitudes in the various load cycles can be determined from the elastic stress analysis. From design requirements the following load cycles per year have to be taken into account

(i) $\Delta\sigma = 45.2 \; Nmm^{-2}$, 25 cycles/year
(ii) $\Delta\sigma = 31.6 \; Nmm^{-2}$, 200 cycles/year
(iii) $\Delta\sigma = 4.5 \; Nmm^{-2}$, 250 cycles/year

Unless the applied stresses exceed the plastic limit load given below, the semi-elliptical surface cracks existing in the weld grow stably through the wall and are then treated as one-dimensional through-wall cracks of the same length as the original surface cracks.

No information was available about the distributions of crack sizes and shapes. For the parameter studies, distributions commonly used in the literature are selected:

$$f(a) = \lambda \cdot \exp(-\lambda \cdot a) \qquad (3)$$
$$\text{with } \lambda = 0.161 \; mm^{-1} \; /7/$$

$$f(a/c) = \frac{1}{\sqrt{2\pi}\,\sigma} \exp\left(-\frac{1}{2}\left(\frac{a/c - \mu}{\sigma}\right)^2\right) \qquad (4)$$

with $\mu = 0.52$, $\sigma = 0.18$ /8/

Plastic instability is expected to be the dominant mechanism for a complete failure of the pipe. As long as the cracks can be described by two-dimensional surface cracks, the limit load is given by

$$\sigma_L = \sigma_f \left(1 - \frac{a \cdot c(2+\frac{a}{R})}{\pi t(2R+t)}\right) \qquad (5)$$

When a crack has grown stably through the wall, eq. (5) has to be replaced by

$$\sigma_L = \sigma_f\left(1 - \frac{c}{\pi R}\right) \qquad (6)$$

The following distribution of flow stress was obtained in /9/:

$$f(\sigma_f) = \frac{1}{\sqrt{2\pi} \cdot \sigma} \exp(- \frac{1}{2} (\frac{\sigma_f - \mu}{\sigma})^2) \qquad (7)$$

with $\mu = 258.9\ N/mm^2$, $\sigma = 18.9\ N/mm^2$

To calculate of the failure probabilities, a new code named PARIS /1/ was used. Compared to existing codes such as the PRAISE code /2/, more fracture mechanical and statistical options are available in the new code (see Table 1). From the point of view of numerics the fundamental difference consists in the way in which the Monte Carlo simulation is performed. In the PARIS-code, importance sampling is used to improve the convergence properties of the simulation and suitable importance functions can be generated by an iterative procedure. PRAISE, on the other hand, uses stratified sampling which has to be adjusted to a specific problem by changing the code /10/.

2. Results

The failure probability of the pipe elbow caused by circumferential cracks in the weld A-B at $\varphi = 122^\circ$ (maximum of elastic stress, see Fig. 2) is calculated as a function of the time. Figure 3 shows the failure probability under the condition that one and only one crack is present. From these results, the following conclusions can be drawn:

- No significant contribution to the failure probability arises from complete pipe severance.
- After some time, the failure probability does no longer increase considerably. This can be explained by the fact that all cracks capable of growing significantly during the time interval considered have become through-wall cracks and are now growing stably.
- At the beginning of the component's lifetime the failure probability is zero because no through-wall cracks exist.
- All the absolute numbers obtained for the failure probability should be considered as not representing the actual reliability of the pipe elbow because they may be changed by orders of magnitude by choice of different distributions for the crack depth a and the aspect ratio a/c.

These conclusions can be verified by considering differential probabilities, e.g. dQ/da which is the probability that one crack of depth a is present in the component and leads to failure. Figure 4 shows dQ/da for the pipe elbow. The sudden rise of dQ/da at a certain value $a_0(N)$ means that all cracks smaller than a_0 do not grow to a crack size relevant to the reliability of the component.

3. Further investigations

In the results described in the previous section some points have been omitted which are currently investigated.

No attempt has been made to include the variation of the stresses along the circumference of the pipe. This is expected to lower the failure probability because stresses are lower at locations different from that considered. All the other welds of the pipe may also contain cracks and contribute to the failure probability. As for the longitudinal welds stresses are very low, whereas the stresses in weld C-D are comparable to those in weld A-B so that the results for the conditional failure probability will not be altered significantly.

Another important point is crack initiation. From the stress analysis /3/ it is known that the crown of the pipe elbow is subjected to much higher stresses than any of the weld So, during the design life of the component, cracks are expected to be initiated because of fatigue of the base material. Whether these cracks will grow significantly within the design life of the component or remain more or less unchanged will influence the reliability of the pipe elbow considerably.

References

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Table 1. Comparison between PRAISE-code and PARIS-code

OPTIONS	PRAISE-CODE	PARIS-CODE
DISTRIBUTED VALUES		
crack depth	exponential + lognormal	exponential lognormal normal weibull gamma uniform constant
aspect ratio	exponential + lognormal	
crack growth parameter	constant + lognormal	
flow stress	constant + normal	
fracture toughness	no	
applied stress	constant	
LOAD		
fatigue	yes	yes
stress corrosion	yes	no
vibratory stresses	yes	yes
earthquakes	yes	no
INSPECTIONS		
proof-test	yes	yes
NDT	yes	yes
leak detection	yes	yes
FAILURE CRITERIA		
linear elastic fract.mechan.	no	yes
plastic instability	yes	yes
two-criteria approach	no	yes
stress intensity factors	1 option	6 options and one user's option
limit load	2 options	
leak-before-break criterion	yes	yes
NUMERICAL PROCEDURE		
simulation	yes	yes
variance reduction	stratified sampling	importance sampling
CRACK GROWTH LAW		
Paris et.al	no	yes
Walker et.al	yes	yes
Forman et.al	no	yes
variation of stresses along the circumference	no	yes

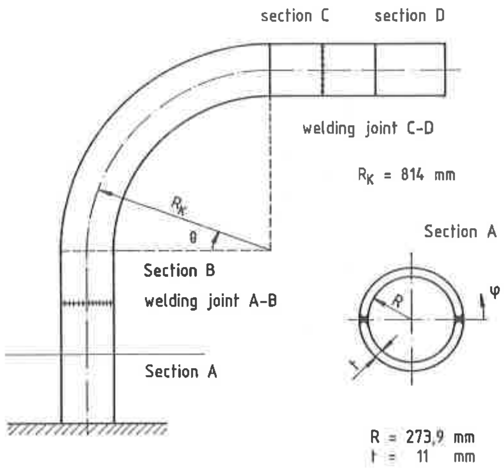

Figure 1: Geometry of the pipe elbow

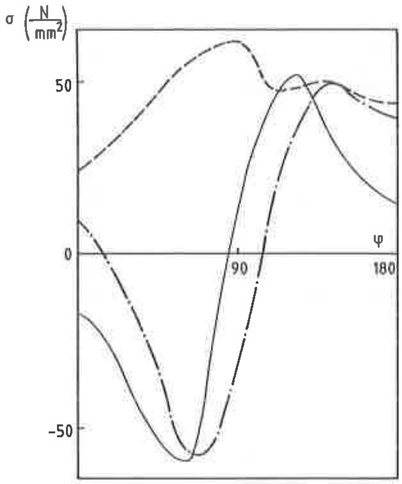

Figure 2: Stresses along the circumference of the pipe, weld A – B

— — — equivalent plastic stress

—.— longitudinal elastic stress, inner surface

——— longitudinal elastic stress, outer surface

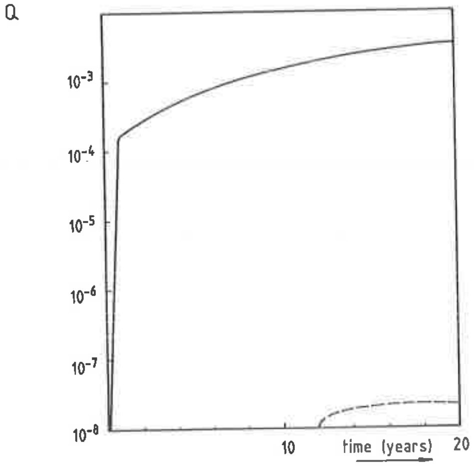

Figure 3: Failure probabilities

——— leak probability

— — — break probability

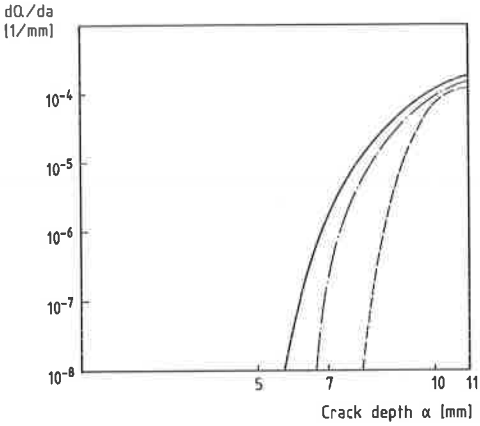

Figure 4: Differential failure probabilities depending on the operating time N

— — — N = 1 year

—.— N = 10 years

——— N = 20 years