FATIGUE FRACTURE OF POWER ENGINEERING STRUCTURES

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Numerical modeling of fatigue fracture process of a pressurized cylinders with surface cracks were carried out. The results of calculations are provided for 60 variants of possible combinations the sizes of the cylinders and an aspect ratio of an initial semi-elliptical cracks. The fatigue life prediction studies were based on a crack growth model using the fracture damage zone approach and the local fracture stress. It is established that the fatigue life of the pressurized a thick-wall cylinder can be expected to be in the order of one tenth of that for thin-wall cylinder. This observable scale effect depends on the aspect ratio and the sizes of initial surface cracks. It has been noted that initial shallow surface flaw tends to stabilize at the aspect ratio between 0.23 and 0.26 depending on the ratio of the wall thickness to inner radius of the pressurized cylinder.

INTRODUCTION

The crack growth in pressurized cylinders is similar in most respects to fatigue fracture and cyclic life in other power engineering structures as pressure vessels or pipelines. Aside from the initiation of cracks due to presence of a corrosive or temperature environment, the growth of cracks in pressurized cylinders is the classic combination of fatigue propagation followed by fast fracture, both of which can be well described using fracture mechanics. As in most other power engineering components the fatigue cracks take on the shape of a part-through or surface crack. So this shape must bear the emphasis in any attempt to characterize the crack growth in power engineering structures.

The purpose of the work reported here, was computational investigation of the influence both sizes and forms of surface cracks on fatigue life in pressurized cylinders.

THEORETICAL APPROACHES

The most important geometric factor to be considered in the description of fatigue crack growth and fatigue life of pressurized cylinders and other power engineering

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components is the semi-elliptical shape which is characteristic of surface cracks. The crack growth of the surface flaw should be calculated in both the depth b into the cylinder wall thickness t and surface $2a$ directions. The ratio between the depth and surface length is referred to commonly as aspect ratio of the crack ε. The type of fatigue crack observed here in Fig.1 is typical of pressurized cylinder where R is inner radius and R_0 is outer one. Therefore the developed computer program which embodies the flaw life prediction method requires an initial crack configuration, the stress intensity factor distribution along the crack periphery, the assumed crack growth model and basic tensile properties of material. A few details of the pipeline material and dimensions are: 20steel with yield stress in the range of σ_0=250MPa, tensile strength of σ_u=420MPa, strain hardening exponent of n=4.18, reduction of area of ψ=55% and wall thickness of 15mm. The geometrical parameters both cylinder and surface crack were varied over the following ranges: $0.1 \le (t/R) \le 1.0$, $0.5 \le (R/R_0) \le 0.91$, $15 \le R \le 150$mm, $30 \le R_0 \le 165$mm, $0.1 \le \varepsilon_0 \le 1.0$, $0.007 \le (b_0/t) \le 0.5$. All cylinders were loaded by nominal stress $\bar{\sigma}_n = \sigma_n/\sigma_0 = 0.7$ then pressure P ranged from 17.16 MPa to 147.1 MPa depending on both inner and outer radiuses.

The life prediction studies in the present work were based on a crack growth model using the fracture damage zone approach and the local fracture stress. Let σ_f be the local fracture stress along the crack front. Its distribution over the crack periphery of the flaw is not, in general, known. For the purpose of the present analysis let us accept that this distribution of local fracture stress σ_f along the crack front in qualitative terms repeat the behavior of the plastic zone. For given the part-through surface crack of nearly half-elliptical shape, it seems reasonable to assume that central and deepest half of the crack front would be governed by conditions of local plane-strain. Then

$$\frac{\sigma_f^{2D}}{\sigma_f^{3D}} = \frac{r_p^{2D}}{r_p^{3D}} \tag{1}$$

and the distribution of σ_f along crack front of semi-elliptical surface crack can be given by following equation

$$\bar{\sigma}_f = \frac{\bar{\sigma}_f^{3D}}{\sqrt{\left(\frac{r_p^{3D}}{r_p^{3D}} \cos\phi_e\right)^2 + \sin\phi_e^2}} \tag{2}$$

where r_p^{3D} and r_p^{2D} are both the plastic zone size in the depth and surface directions, ϕ_e - is a parametrical angle of ellipse. It can be noted that $\bar{\sigma}_f^{3D} \approx \bar{\sigma}_u^{true}$ (the true ultimate stress), i.e. $\bar{\sigma}_u^{true} = \sigma_u/\sigma_0(1-\psi)$, where σ_0 is the yield stress and ψ is the reduction of area.

A critical distance r_c (fracture damage zone size) ahead of the crack tip is assumed to be located where the stress strain state in an element reaches a certain critical value that cam be measured from a uniaxial test. A relative fracture damage zone (FDZ) size $\bar{\delta}_c = r_c/a$ was introdused in work (1) as

$$\bar{\delta}_c = \left\{ \frac{\bar{S}_2 \pm \left[\bar{S}_2^2 - 4\left(\bar{W}_c^* - \bar{S}_3\right)\left(\bar{S}_1 + \bar{S}_p\right) \right]}{2\left(\bar{W}_c^* - \bar{S}_3\right)} \right\}^2 ;$$

$$\bar{W}_c^* = \left(\frac{\sigma_0}{\sigma_{yn}} \right)^2 \left[\frac{1}{2} \bar{\sigma}_f^2 + \frac{\alpha n}{n+1} \bar{\sigma}_f^{n+1} \right] \tag{3}$$

where α and n are strain hardening coefficients. Application of eq.(2) together with eq.(3) leads to a following relation for fatigue crack growth rate

$$\frac{da}{dN} = 2\bar{\delta} a \left(\frac{\sigma_n^2 \bar{K}_f - \sigma_{th}^2 \Delta \bar{K}_{th}}{4\sigma_f^* \varepsilon_f^* E \bar{\delta}} \right)^{\frac{1}{m}} \tag{4}$$

where $\bar{K}_f = \bar{S}_1 + \bar{S}_p + \bar{S}_2\sqrt{\bar{\delta}} + \bar{S}_3\bar{\delta}$ and $\bar{S}_i\left(i = 1,2,3\right)$, $\bar{S}_p$ are dimensionless functions of elastic and elastic-plastic stress intensity factors. In equation (4) $\Delta\bar{K}_{th}$, σ_f^*, ε_f^*, m are the experimental constants.

The proposed model (4) assumes that the growth variation can be modeled by assuming different growth rate properties in the depth and surface directions. Assuming crack growth increment, r_c, to be small, the stress intensity factor of the i^{th} load event is given as

$$\Delta K_i = F\left(\Delta\sigma_i, a_{i-1}, Y\left(a_{i-1}\right)\right) \tag{5}$$

where $\Delta\sigma_i$ is stress range of the i^{th} event, a_{i-1} is the terminal crack size of previous $\left(i-1\right)^{th}$ load event, and Y interrelates crack geometry to the configuration of the part. Solution for Y of many common-engineering configurations is tabulated in handbooks. The following two-dimensional (that is, the crack was assumed to grow at a varies aspect ratio) stress intensity solution by Newman and Raju (2) for surface crack was used in the presence analyses

$$K = \frac{PR}{t}\left(\frac{\pi b}{Q}\right)^{\frac{1}{2}} F_e\left(\frac{b}{a}, \frac{b}{t}, \frac{t}{R}, \phi\right) = \sigma_n\sqrt{\pi b}\,Y\!\left(Q^{-\frac{1}{2}}, F_e\right), \quad Q = \sqrt{1 + 1.464\left(b/a\right)^{1.65}} \tag{6}$$

Since the stress intensity factor varies around the crack front and state of stress also varies, flaw shape change (aspect ratio variability) should be considered in any part-through crack life analysis. The crack growth is calculated in both the depth, *b*, and surface, *a*, direction simultaneously while accounting for the change in *Q* as the flaw shape changes. This computational process continues until a terminal value of crack size is reached. For the pressurized cylinder terminal flaw size may be the "leak-before-break" condition at breakthrough.

RESULTS AND DISCUSSION

The crack growth is calculated by using eq.(3) in 90 points around the crack periphery for each combination varied parameters of geometry of cylinders and part-through cracks. The initial aspect ratio is varied from semi-elliptical shape (ε_0=0.1) to semi-circular (ε_0=1.0) one. In many observations of surface flaw crack growth under tension loading, it has been noted by the author that the surface flaw tends to stabilize at some value of aspect ratio depending on the material loading. As it follows from Fig.2 stabilization of flaw shape takes place only for shallow initial cracks. This approximate value of ε=0.245 is achieved for any initial values of $\varepsilon_0 = \mathbf{b/2a}$. For intermediate and deep initial cracks (Fig.3) it does not occur.

In our calculations were wide ranges for both the crack size and aspect ratio. It is established that there is significant variation in aspect ratio with crack size depending on cyclic loading. Figure 4 graphically illustrate that this difference in initial aspect ratio leads to a considerable difference in current flaw shape depending on number of cycles of loading. Three such crack growth steps can be seen in Fig.4, the last of which caused the final breakthrough to the inner surface of the pressurized cylinder.

It is a well known fact that the shape of the part-through crack may vary during the crack growing process. The need to account for the shape change effect in analytical prediction procedure is obvious. However the fatigue crack growth in the pipeline has the peculiarities. As it follows from the Fig.5 initial extended (narrow) semi-elliptical surface cracks to grow long time under cyclic loading at constant value of the aspect ratio. The crack growth much more rapidly for depths beyond mid-wall. Moreover the crack growth rate in the depth direction is faster than the crack growth rate in the width direction. Another situation takes place for the initial semi-circular surface cracks. The change of their shape occurs during all period of cyclic loading and more intensively for initial deep cracks. Beside the crack growth rate in the surface direction is faster than the crack growth rate in the depth direction.

Equation (4) together with equation (3) was used to calculate the curves in Figs.5 and 6. The crack growth calculations plotted in Fig.6 are shown the significant effect of both crack shape and cylinder size on growth rate and cyclic life. As it follows from Fig.6 the fatigue life of the pressurized the thick-wall cylinder can be expected to be in the order of one tenth of that for thin-wall cylinder. This observable scale effect depends on the aspect ratio and the sizes of initial surface cracks. So it is clear that their effect in pressurized cylinders must be included for an accurate description of the fatigue crack growth and life behavior.

REFERENCES

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SYMBOLS USED

2a = crack length along the cylinder surface

b = crack depth into the cylinder wall

$\mathbf{N_b}$ = fatigue life

$\mathbf{r_p}$ = plastic zone size

R = inner radius

$\mathbf{R_0}$ = outer radius

t = wall thickness

δ = fracture damage zone size

ε = aspect ratio

σ_f = local fracture stress

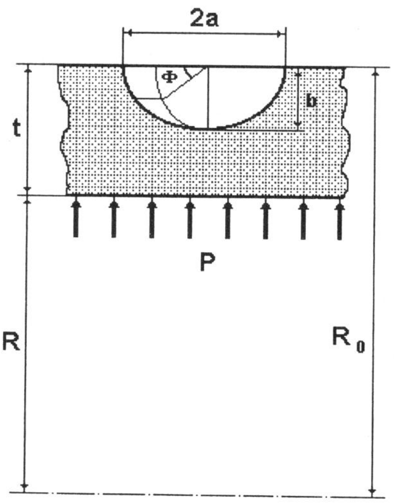

Figure 1 Geometry for part-through crack in pressurized cylinder

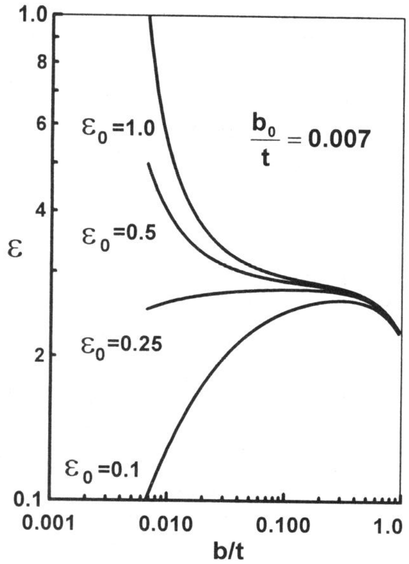

Figure 2 Aspect ratio change prediction for shallow surface cracks

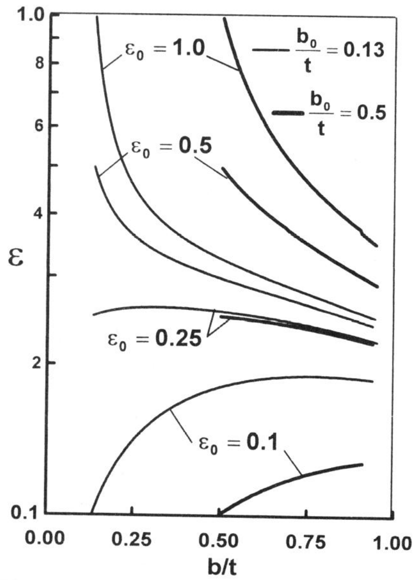

Figure 3 Aspect ratio change prediction for middle and deep surface cracks

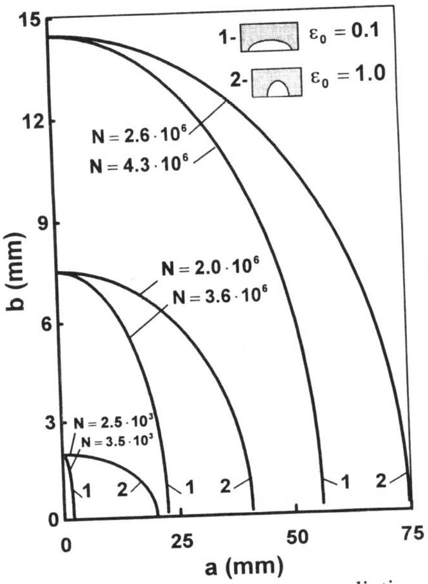

Figure 4 Flaw shape change predictions

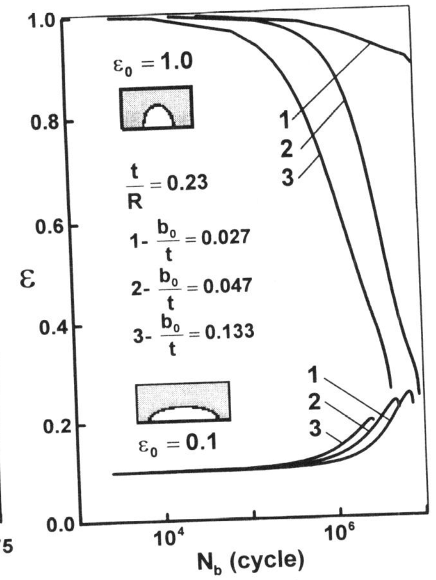

Figure 5 Aspect ratio change versus fatigue life

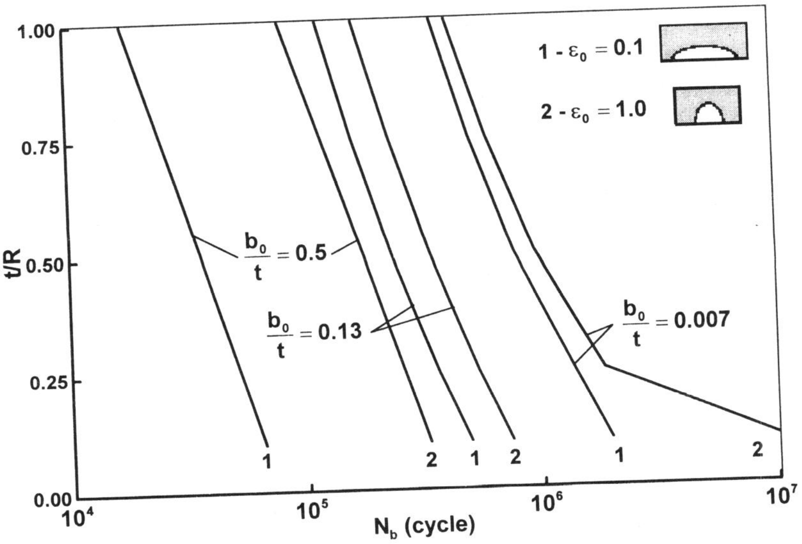

Figure 6 Fatigue life prediction of pressurized cylinders with surface cracks