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Remaining Fatigue Life of a Spherical Joint

Durée de vie restante d'un joint sphérique

Restlebensdauer sphärischer Knoten

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SUMMARY

The investigation of the remaining fatigue life of a spherical joint is based on the evaluation of a conical fatigue crack growing from the sphere to tube weld. An attempt is made to optimize the geometrical parameters of the joint in order to improve remaining fatigue life.

RÉSUMÉ

Le problème de la durée de vie restante d'un joint sphérique est basé sur l'évaluation d'une fissure de fatigue cônique se propageant depuis ce joint dans la soudure du tube. Une tentative d'optimisation des paramètres géométriques du joint a été faite dans le but d'en améliorer la durée de vie restante.

ZUSAMMENFASSUNG

Anhand der Beurteilung eines konischen Ermüdungsrisses, der von einer Kugel-Rohr-Schweissverbindung ausgeht, wird die Restlebensdauer eines sphärischen Knotens untersucht. Es wird versucht, die geometrische Form zu optimieren und dadurch die Ermüdungsfestigkeit solcher Verbindungen zu erhöhen.

1. INTRODUCTION

The Limit States Method, introduced in Czechoslovak Specifications for Structural Steel Design in 1969, was applied in case of dimensioning and reliability assessment of a 340 m high guyed latticed tubular steel TV mast located near Plzeň. Special attention was paid to the investigation of the actual behaviour of welded joints (especially of the details like tubes welded to spherical nodes) exposed to fatigue. The information on response history, results of experimental investigation and on the final set up of the TV mast are discussed in [1].

The experimental study on fatigue strength of spherical joint was followed by a pilot study on crack propagation. The definition of the applied model based on the linear fracture mechanics and FEM is summarized in [2].

The steps following the pilot studies on the actual fatigue strength of spheric joints, mentioned above, were focused on the residual fatigue life and optimization of the geometrical proportion of spheric joint. The results are subject of this paper.

2. RESIDUAL FATIGUE LIFE OF THE CRACKED SPHERICAL JOINT

2.1 The formulation of the problem

In order fo formulate the problem, the experimental facts are summarized first:

During testing, the equivalent loading was represented by a force with amplitude of 350 kN and mean value of 250 kN. The crack was detected after 129 000 loading cycles and final fracture of the brittle type occured after approximately 150 000 loading cycles. On the basis of the fractographic study of the fractured surface of the failured spherical joint, the direction and the form of the fatigue crack were determined.

The sectional view of the spherical joint is given in Fig. 1. In accordance with the experimental set up, the boundary conditions for fatigue life calculations are modelled as follows (Fig.2): The external load is simulated by a constant stress σ acting on the tube in Z direction, the displacements in R direction equal to zero for the edge A and displacements in R direction equal to zero for the edge B of the sphere. The crack propagation direction is given by the angle α and crack grows along the surface of the cone created by rotation of the straight line p around the Z axes. The crack length a is measured along the straight line p (Fig.2).

On the basis of the above assumptions, the problem can be solved as an axialsymmetric one and for description of the stress state in the vicinity of the crack tip the plane strain approximation can be used.

In the following paragraphs the results are presented for the remaining fatigue life of the cracked spherical joint with the preexisting crack of the length a_0. The computation is based on

$$\frac{da}{dN} = C.(\Delta K_I)^m \qquad (1)$$

where ΔK_I is a range of the stress intensity factor.

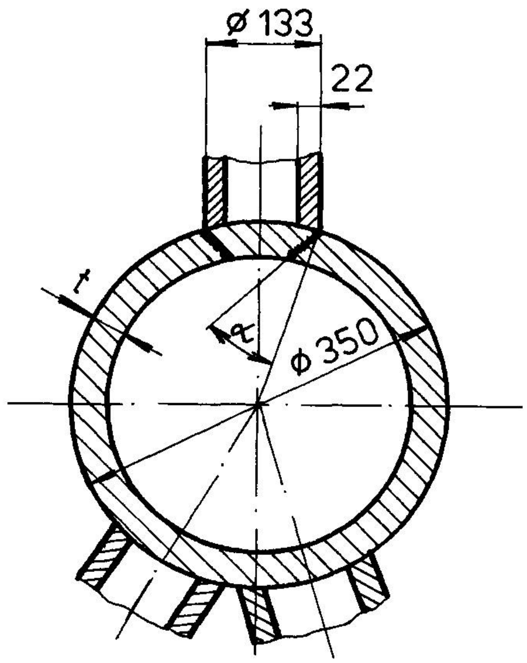

Fig.1 Sectional view of the spherical joint with conical crack

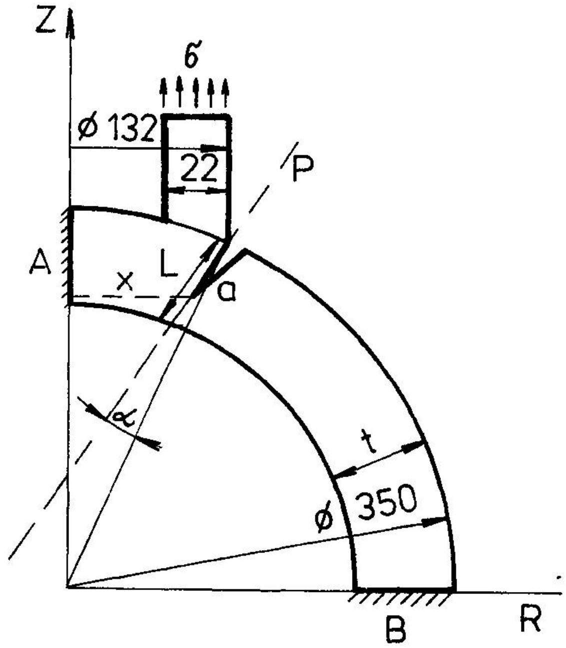

Fig.2 Numerical model used for FEM calculations

To this aim, the K_I calibration curve is calculated. Computations were performed by means of finite element method as implemented in PROKOP code [3].

2.2 K - calibration calculation

K - calibration curve, i.e. the dependence of the stress intensity factor K on the crack length a, was for our problem obtained by calculation of a strain energy release rate G(a)

$$G(a) = \delta U(a) / \delta a \ , \tag{2}$$

where δa is a crack length increment causing a release of strain energy of amount δU. The stress intensity factors K_I (opening mode I) and K_{II} (shearing mode II) are directly related to the value of δU by equation (for plane strain)

$$G = (1 - \nu).(K_I^2 + K_{II}^2) \ / \ 2\mu \ , \tag{3}$$

where ν, μ are Poisson's ratio and shear modulus respectively.

K_I, K_{II} is calculated from (3) by means of procedure suggested in [3].

For δU calculation the method is used based on finite element design sensitivity analysis as implemented in PROKOP code [5].

The crack growth is modelled by means of a double noding technique [5]. The loading and boundary conditions correspond to those formulated in 2.1.

The calculated K_I calibration curve can be approximated by the formula (for $0,15 \leq a/L \leq 0,8$)

$$K_I = \sigma . \sqrt{\pi a} . \left[8,178 \left(\frac{a}{L}\right)^{1/2} - 14,80\left(\frac{a}{L}\right)^{3/2} + + 11,13.\left(\frac{a}{L}\right)^{5/2}\right], \qquad (4)$$

where σ is applied external stress acting on the tube (see Fig.2), $L = 34,61$ mm, $t = 30$ mm, $\alpha = 27^0$.

For the corresponding K_{II} value it holds (for $0,1 \leq a/L \leq 0,8$)

$$K_{II} \leq 0,06\ K_I \qquad (5)$$

and so K_{II} values have practically no influence on the fatigue crack propagation rate and on the remaining fatigue life as well.

2.3 Results

The remaining fatigue life N_f was then calculated by integration of Paris law (1) between initial crack size a_0 and a chosen size a_f (for $m = 2,37$, $C = 5,70.10^{-11}$, da/dN [m/c], ΔK [$MPa.m^{1/2}$]) - see [2].

3. INFLUENCE OF THE SPHERICAL JOINT GEOMETRY

3.1 A fracture mechanics approach to the optimum design of structures [6]

In conventional strength calculations for loaded structures, usually the requirement is made, that a calculated stress should not exceed a critical value (e.g. design stress). If the main task of optimization is to improve conventional safety of the structure, the objective function is created from this point of view.

Evidently, in the case of structures weakened by cracks, the above conventional approach is no longer applicable and results of fracture mechanics should be taken into account.

The aim of the present chapter is to use the fracture mechanics as a tool for shape optimization of the spherical joint with respect to fatigue failure and remaining fatigue life.

3.2 Formulation of the optimization problem

The basic idea of fracture mechanics optimization is to decrease the probability of fracture by changes of geometry of structures under consideration.

The aim of our procedure is to increase the remaining fatigue life N_f (a_0, a_f) of the spherical joint.

The value of N_f depends on geometry of structure Γ, material properties M, history of the response of the structure to external loading F and boundary conditions B. For the given boundary conditions B, history of response F and material properties M the crack trajectory and, remaining fatigue life N_f as well, depends on the geometry of the structure only

$$N_f = N_f . [A(\Gamma)] , \tag{6}$$

where $A(\Gamma)$ describes the crack trajectory.
The optimization procedure can be formulated as

$$N_{max} = \max_{g_i} N_f [A(\Gamma)] , \tag{7}$$

where set of parameters g_i (describing the geometry Γ) creates design variables

$$g_i \in \Gamma . \tag{8}$$

Constraints for g_i follow from construction requirements and moreover have to prevent other types of construction collapse. In order to solve the problem, it is required with regard to each structure :

(1) To determine the initial crack propagation direction it may be supposed, that the location of the crack initiation is known.

(2) For the given initial crack to find numerically its trajectory $A(\Gamma)$ (i.e. crack propagation tracking).

(3) For the given crack trajectory $A(\Gamma)$ to calculate the values of the stress intensity factors (i.e. corresponding K - calibration curves) and remaining fatigue life N_f $[A(\Gamma)]$.

It is evident, that the formulated optimization problem is too complicated and cannot be completely solved. But, following the basic ideas of the procedure, some very useful conclusions for the design of structures can be obtained.

With respect to this fact, we have limited our considerations on the study of the influence of the sphere thickness t (see Fig.2) on the residual fatigue life N_f of the spherical joint. Supposing that the crack is initiated at the joining weld between tube and sphere, the dependence

$$N_f = N_f (t) \tag{9}$$

can be calculated for particular orientation of crack - see next paragraph.

3.3 The orientation of the pre-existing crack

For the determination of the pre-existing crack orientation the energy criterion is used. Accordingly, the crack will propagate in direction $\alpha = \alpha_m$ identical to the direction of the minimum of the strain energy density w :

$$w(\alpha_m) = w_{min}(\alpha) . \tag{10}$$

Strain energy density w is determined on the basis of finite element calculations and the eq. (10) is solved numerically. The computations were done for $a_0 = 1,7$ mm.

As a result, the dependence $\alpha_m = \alpha_m(t)$ is given in Fig.3.

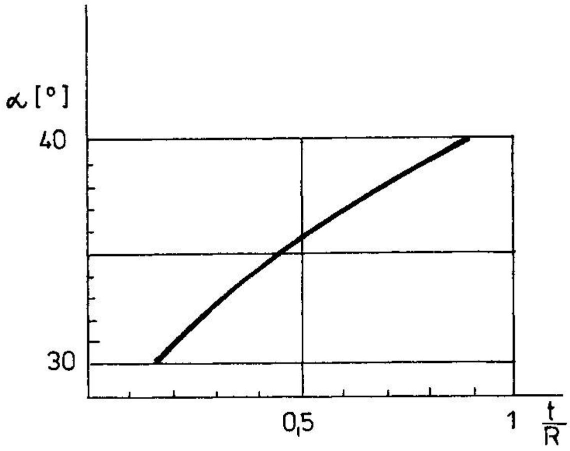

Fig.3 Dependence of crack propagation direction on sphere thickness t (R = radius of the sphere)

3.4 The determination of the fatigue crack trajectory

Generally, the fatigue crack initiated at the weld will propagate under mixed mode I and II conditions. In consequence of it, the crack trajectory have to be calculated first.

An essential ingredient of a crack propagation tracking is a criterion to predict the direction of crack propagation. Numerous past investigators have studied the problem, but there are still some disagreements among the various theoretical approaches (see e.g. [7]). In presented considerations, the strain energy density criterion as suggested by Sih - S criterion (e.g. [8]) is used. Following this criterion, the crack propagation direction depends on the ratio K_{II}/K_I and if $K_{II} \rightarrow 0$ the crack propagates directly along the straigt line.

For crack lengths in the interval $a_o < a < 10$ mm, the ratio $K_{II}/K_I \leq 0,05$. So, as the first approximation let be supposed, that the crack trajectory is not influenced by mode II loading and crack propagates along the surface of the cone as in Chapter 2. Geometry of the cone is given by the value of $\alpha_m(t)$.

This approximation holds good for relatively short crack length ($a \leq 10$ mm). For crack length $a > 10$ mm and especially for ratio $t/R \rightarrow 1$ (full sphere) and for more exact calculations the real crack path should be taken into account.

In the following paragraph it is supposed for all calculated cases, that the crack trajectory creates a cone. The changes of the sphere thickness t influence the angle α_m only.

3.5 K - calibration curves for spherical joint with different sphere thickness

Based on the same procedure as in 2.2 the K_I calibration curves were calculated for various values of the sphere thickness t. Results hold in the crack length interval 1,7 mm to 25 mm.

3.6 Remaining fatigue life calculations

The remaining fatigue life N_f (a) is calculated by integration of Paris equation (1). As the ratio K_{II}/K_I changes slightly, K_I values can be taken as the parameter controlling the crack propagation rate. The value K_{II} has influence on the crack trajectory only [9].

3.7 Results

Using the same procedure and material characteristics as in the Chapter 2., the remaining fatigue life for various values of the sphere thickness (t = 30, 60, 90, 120, 150 mm) were calculated. To illustrate the influence of t on the remaining fatigue life of the spherical joint, the results for two limiting cases (t=30mm and t=150 mm) and initial crack length 2 mm and 15 mm are presented in the Fig. 4.

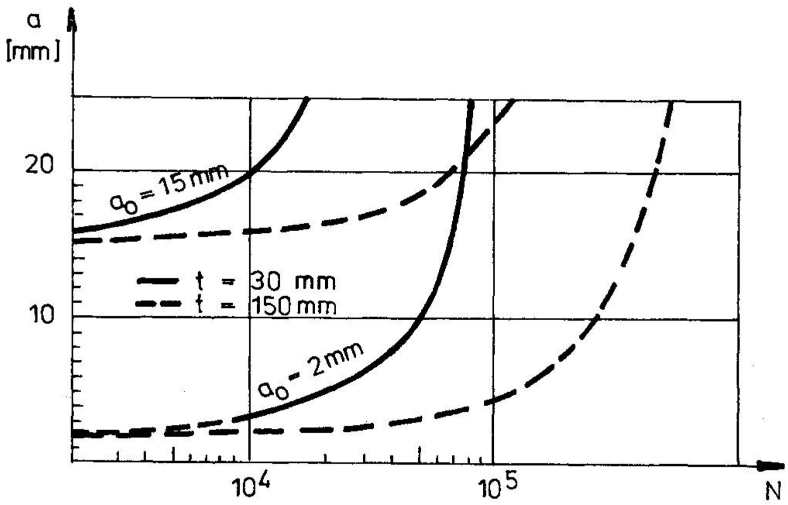

Fig.4 Remaining fatigue life of the spherical joint for two limiting thickesses t (a_o = initial crack length, N = number of cycles)

4. CONCLUSIONS

Linear elastic fracture mechanics and finite element method allow the evaluation of the remaining fatigue life of the spherical joint. With the aim to optimize the geometry of the joint, the influence of the sphere thickness on the fatigue life was studied. From this point of view, the full sphere of the joint gives the best results.

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