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Working life estimate of the tubular T-joint by application of the LEFM concept

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Abstract

The crack growth in tubular joints usually occurs along the weld's toe. That is the point where the chord and brace intersect. The semi-elliptical crack appears in this area from the initial flaw that was created during the welding. Sensitivity to fatigue depends on combination of cyclic loading, initial defects, environmental influences and the hot spot stresses, which are result of the walls' bending during the loading of a structure. The principles of the linear elastic fracture mechanics (LEFM) are applied here to crack growth in the tubular T-joint, subjected to axial load, in-plane and anti-plane bending. Influences of the level and type of loading, as well as of the joint's geometrical characteristics, on the fatigue crack propagation and consequently on the working life of the welded joint, are considered. Based on the conducted analysis, which implies a set of assumptions, one can draw sufficiently relevant conclusion on the remaining working life of the tubular T-joint. The assumptions included: the crack shape is semi-elliptical, there is only one crack propagating through the tube wall, the cyclic plastic zone at the crack tip is small with respect to other geometrical variables and the crack grows only if the difference between the stress intensity factor values at maximal and minimal loads is greater than the stress intensity factor necessary for the fatigue crack growth initiation. Results are presented in the form of diagrams from which can be seen that for the same load level the longer working life is achieved for the axial load of the joint than for the in-plane bending, while the values for the anti-plane bending lie between these two limiting results.

Keywords: tubular T- joint; fatigue crack; Paris law; LEFM

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1. Introduction

In steel components, primarily in welded structures, the cracks appear mainly in the semi-elliptical shape. Fracture mechanics can be used as a method for predicting the remaining working life of such a component, where it is necessary to determine the stress intensity factor for this type of a crack and the corresponding loading. As Lee et al. (2009) pointed out: "the advance in welding material and technology makes it easy to control weld geometry such as weld profile, weld throat thickness and weld flank angle. The improvement of fatigue life by means of weld geometry control can be obtained by reducing stress concentration at welds since weld geometric parameters have direct influence on the stress intensity factor, which is the most important factor determining fatigue strength".

The sensitivity to fatigue can be estimated in two ways. The first is the empirical S-N method that defines the relationship between the rank of the applied loading and the fatigue working life of an element; the second method is based on the linear elastic fracture mechanics principles. It considers the growth rate of existing defects in each phase of their expansion and is the most convenient for estimating the remaining working life of welded structures.

The welded joints resistance, from the fracture mechanics aspect, was the subject of research of certain number of researchers: Atzori et al. (1999), Motarjemi et al. (2009), Baik et al. (2011), Chattopadhyay et al. (2011), Shen and Choo (2012), Carpinteri et al. (2015), Maheswaran and Siriwardane (2016), Carpinteri et al. (2017) etc.

The principles of the linear elastic fracture mechanics (LEFM) are applied in this paper for determining the behavior of the fatigue crack growth in tubular joints. That enables considering the influence of various parameters (load, geometrical characteristics, fatigue crack propagation, etc.) separately and independently. It is also possible to estimate the share of the fatigue crack growth and thus the working life of the welded joint.

2. Problem formulation

The fatigue fracture appears as a consequence of exposing the component to cyclic loading. There are three phases of the fatigue fracture: crack initiation, crack growth and fracture. The crack can appear due to the surface defect on the component caused by the manual or machine processing, threading or due to phenomena of slip bands or dislocations caused by previous cyclic loading or overloading. During the crack propagation phase, it continues to grow due to loads to which it is exposed. The fracture phase occurs abruptly and it happens when the portion of the component that does not contain a crack cannot withstand the applied loads.

The fracture mechanics can be used in the analysis of fatigue since it predicts the crack growth rate within the component and thus the remaining working life of a component. It gives the relationship between the stress and deformation states around the crack tip and the geometric parameters, applied loads and crack length. The stresses at the crack tip can be written as, Irwin (1957):

$$\sigma_{ij} = \left(K/\sqrt{2\pi r}\right) f_{ij}(\theta), \tag{1}$$

where: r and θ – are the polar coordinates, defined by Williams (1959). The intensity of the stress field ahead of the crack tip can be described aby a single parameter K, the stress intensity factor. That is the most important parameter in application of the fracture mechanics for analysis of the fatigue problems. The stress intensity factor depends on the shape of the component and the way of loading.

For the welded joints, the stress intensity factor can be, in general, be calculated according to, Hobbacher (1993):

$$K = Y \cdot M_k \cdot \sigma_n \sqrt{\pi a}\ , \tag{2}$$

where: σ_n is the referent loading (axial tension, bending or torsion), a is the crack length, Y is the dimensionless parameter that depends on the sample (component) geometry and applied load, while M_k is the correction factor, which takes into account the stress concentration due to the presence of a weld.

The stress intensity factor K controls the crack propagation and the size of the plastic zone around the crack tip. If the plastic zone or the applied load were of the order of magnitude of the crack size or the yield stress, respectively, the LEFM assumptions would not be valid, due to excessive plasticity at the crack tip. However, the plastic zone size in cyclic loading is usually smaller than in monotonic loadings, so the application of the LEFM concept for analysis of the fatigue crack growth is justified, ASM Handbook (1986).

Geometry and loading of the considered tubular T-joint are presented in Fig. 1. Assumptions for calculations of this component's fatigue life are the following: the crack shape is semi-elliptical, there exists a single crack only, which propagates through the tube's wall thickness and the crack is in the joining area of the weld and the base metal.

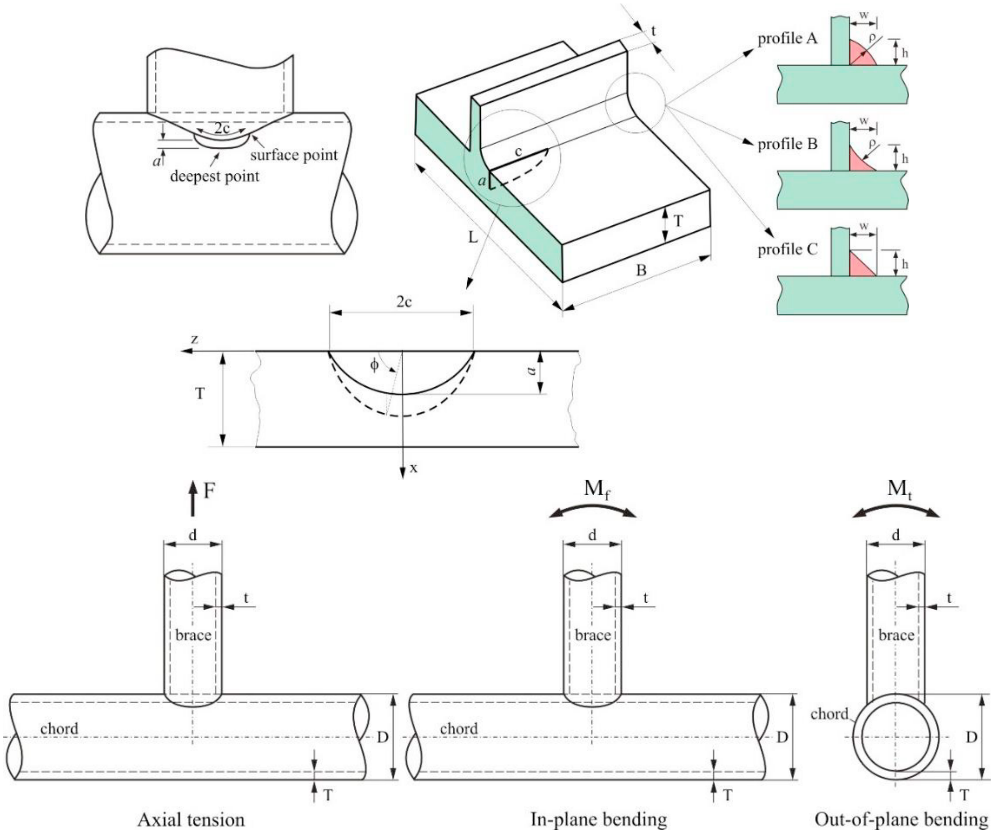

Fig. 1. Tubular joint with semi-elliptical crack along the weld toe: geometry and loading

In Fig. 1 are presented three shapes of the weld: the convex (profile A) and concave (profile B) with radius ρ and the triangular (Profile C), where h is the weld's height and w is the weld's width. The chord's diameter is D and the wall thickness is T, while the brace's diameter is d and the wall thickness is t. The semi-elliptical crack's depth is a and the length is c. Three types of loading are considered: axial tensile (AT), in-plane bending (IPB) and out-of-plane bending (OPB). The normal stress σ_n in the brace is

$$\sigma_n = P\Big/\left\{\pi[r^2-(r-t)^2]\right\} \text{ for axial loading,} \tag{3}$$

$$\sigma_n = 4rM_f\Big/\left\{\pi[r^4-(r-t)^4]\right\} \text{ for in-plane bending,} \tag{4}$$

$$\sigma_n = 4rM_t\Big/\left\{\pi[r^4-(r-t)^4]\right\} \text{ for out-of-plane bending,} \tag{5}$$

where F, M_f and M_t are the axial force, bending moment and torque of the brace, respectively.

The dimensionless parameter, Y, for the axial loading, in-plane and out-of-plane bending, is defined by Rhee et al. (1991). The correction factors, M_k, which take into account the stress concentration due to existence of the weld, for various loading types, are defined by Niu and Glinka (1987) and in the JSSC report #32 (1995).

The unstable crack growth occurs when the stress intensity factor K_I becomes greater than the material characteristics - the fracture toughness K_{Ic}. The crack growth equation for the cyclic loading gives the relationship between the crack length Δa and increase of the number of loading cycles ΔN. Paris and Erdogan (1963) have established that the change of the stress intensity factor ΔK can describe the subcritical crack growth in the fatigue loading conditions in the same way as does the stress intensity factor K for the critical or the fast fracture. They determined that the crack growth rate is a linear function of the change of the stress intensity factor ΔK, in the logarithmic diagram, i.e.:

$$\left(da / dN\right) = C(\Delta K)^m , \tag{6}$$

where: da is the crack length change, from the initial to the critical value, which leads to fracture, N is the number of loading cycles, while C and m are the material constants and $\Delta K = K_{max} - K_{min}$ is the change of the stress intensity factor (the difference between its values at the maximal and minimal loads).

The remaining working life of the cracked component is obtained by integration of equation (6) as:

$$N = \int_{a_i}^{a_{cr}} da \big/ C(\Delta K)^m , \tag{7}$$

where: a_i is the initial and a_{cr} is the critical crack length.

3. Results and discussion

Variation of the normalized Mode I stress intensity factor in terms of the relative crack length a/T, for three considered cases of loading, are shown in Fig. 2, with SIF being normalized with the normal stress σ_n.

From Fig. 2 can be seen that the normalized Mode I stress intensity factor increases as the crack propagates until it reaches about 50 % of the wall thickness and then it starts to decrease. It can also be seen that the values of the normalized Mode I stress intensity factor for the in-plane bending are significantly smaller than values for the axial loading or the out-of-plane bending. This is explained by the fact that the "hot-spot" stresses (structural stresses) are the highest for the in-plane bending.

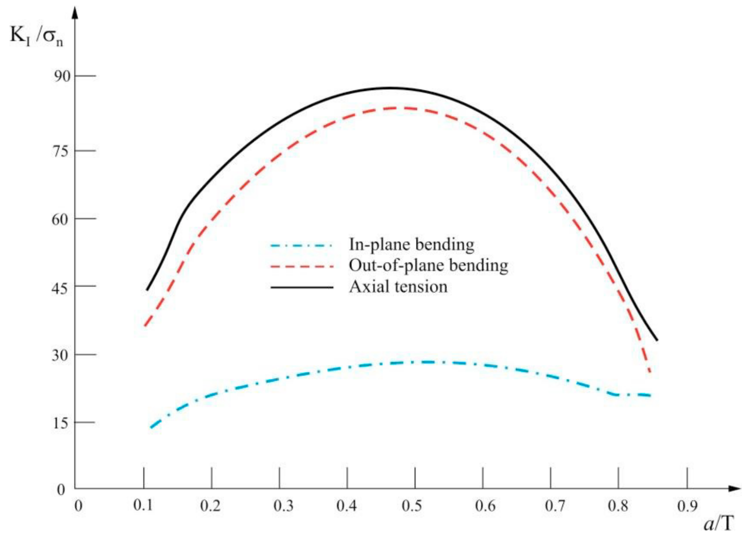

Fig. 2. Normalized SIF as a function of the normalized crack depth at the deepest point (DP).

The variation of the crack growth rate in terms of the relative crack depth is presented in Gif. 3 for the three considered cases of loading. The diagram is obtained by use of equation (6) and application of the programming package *Mathematica*®. The material characteristics used in this analysis are: E = 210 GPa and ν = 0.3, while the material constants necessary for calculation of the component's working life are: m = 3, C = 2.92×10^{-12}. The geometrical parameters (see Fig. 1) are d/D = 0.5, t/T = 1, ϕ = 45°, c = 50 mm.

From Fig. 3 one can see that the crack growth rate is large at the beginning then the crack grows slower and at the end it again starts to grow rapidly, for all the three cases of loading. This type of behavior corresponds to the three phases of the fatigue crack growth.

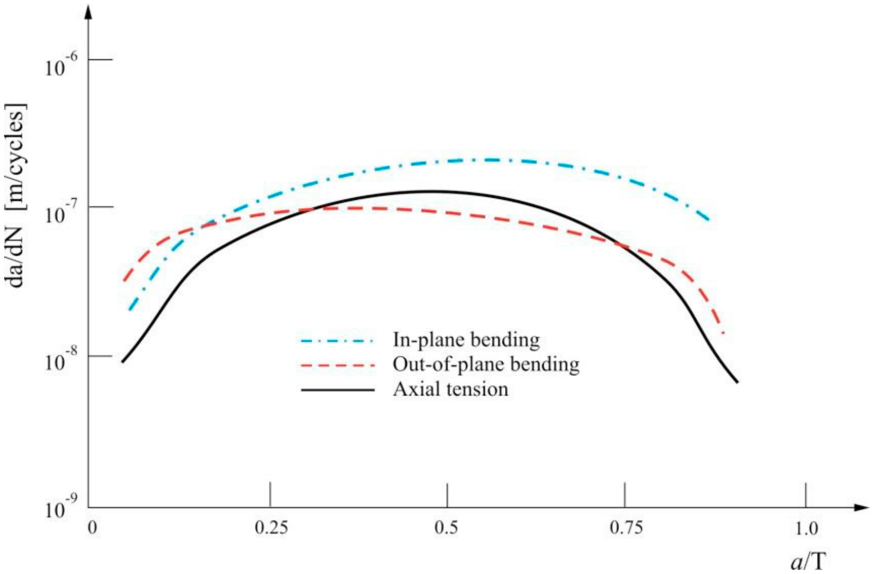

Fig. 3. Dependence of the crack growth rate on the relative crack depth

The variation of the fatigue working life, i.e. the number of loading cycles of the tubular T-joint, is presented in Fig. 4, as a function of the relative crack depth, for the three considered cases of loading. From Fig. 4 can be seen that, for the same level of loading, the longest fatigue working life the T-joint has for the axial loading and the shortest for the in-plane bending, while for the case of the out-of-plane bending the values are between the other two curves.

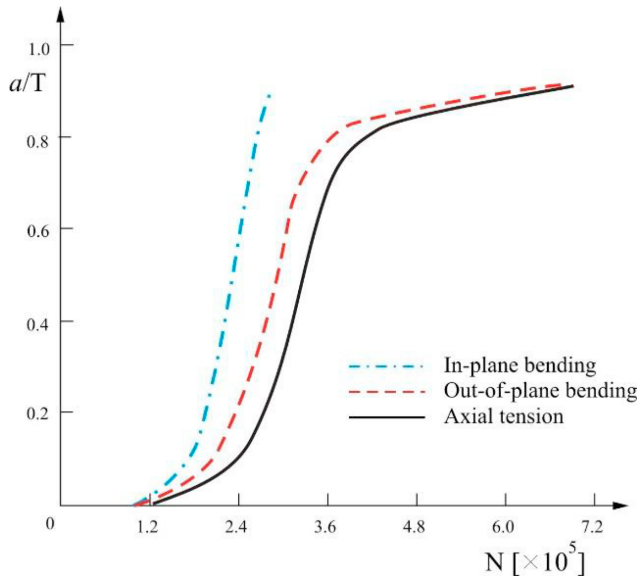

Fig. 4. Fatigue working life of the tubular T-joint for the three cases of loading

4. Conclusions

The principles of the Linear Elastic Fracture Mechanics are applied in this paper for analysis of the fatigue crack growth of tubular T-joints. Based on analysis, conducted in this research, despite a number of assumptions, one can draw a relevant conclusion about the remaining fatigue working life of such joints.

The stress intensity factor for the three considered cases of loading (axial, in-plane and out-of-plane bending) increases with increase of the relative crack depth up to about 50 % of the tube wall thickness and then it starts to decrease; with increase of the load level the working life is decreasing, what is an expected result, since the Mode I SIF is primarily responsible for the crack growth. It can also be concluded that the crack growth rate is initially increasing, then its growth is slow, while at the end it again increases rapidly, what corresponds to the crack growth phases (initiation, stable growth and fracture). For the same load level the axially loaded joint would have the longest working life and the in-plane bent joint would have the shortest, while the values for the out-of-plane bending are between these two limiting cases.

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