ANNALS of Faculty Engineering Hunedoara – International Journal of Engineering
Tome XIV [2016] – Fascicule 2 [May]
ISSN: 1584-2665 [print; online]
ISSN: 1584-2673 [CD-Rom; online]
a free-access multidisciplinary publication of the Faculty of Engineering Hunedoara

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RESIDUAL LIFE EVALUATIONOF A THREADED ROUND BAR WITH SURFACE CRACK UNDER CYCLIC LOADING

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ABSTACT: A computational procedure is formulated in order to investigate the propagation of surface crack in a threaded round bar. The fatigue strength calculation includes the stress analysis and fatigue life calculation. The authors employed the crack growth law based on a two-parameter driving force model for the residual strength evaluation. The estimations are compared with available experimental data. The computed results are in a good agreement with experimental observations.
Keywords: fatigue, threaded round bar, surface crack, life calculation

1. INTRODUCTION

Continuous exploitation could reduce the strength of mechanical structures through appearance of initial cracks as they most often propagate under cyclic loading. In general, such flaws can be approximated either as through-the-thickness crack or surface crack (embedded, semi-elliptical, corner crack). The present paper examines the propagation of semi-circular crack initiated in a threaded round bar.

Within the context of fracture mechanics and in order to ensure the integrity of structural components, an important aspect is to develop and implement reliable computational procedures for residual life estimation. The fatigue strength assessment demands the implementation of adequate crack growth laws. In the literature, there is a number of different crack growth concepts for the crack growth rate simulation and the life calculation under cyclic loading. Service loading conditions, as a interaction of both an alternating load and a mean load, cause impact on fatigue crack growth behavior and different crack propagation mechanisms/models are developed such as: crack closure [1], partial crack closure [2], residual compressive stresses [3], two-parameter driving force model [4, 5].

Furthermore, the geometry of surface flaws together with external loading are taken in the crack growth estimation by introducing stress intensity factors through the stress analysis. The fracture factor can be theoretically investigated by employing different methods such as: the boundary integral equation method [6], the alternating method [7, 8], the finite element method with singularity elements [9], the finite element alternating method [10] and the finite element method with displacement hybrid elements [11].

The aim of this paper is to develop the computational model for the crack growth analysis of the threaded round bar with surface crack. In the crack growth estimation, the stress analysis and the fatigue life calculation are examined. The stress analysis is performed by applying analytical approach. Further, the residual strength of surface crack configuration is estimated by employing the two-parameter driving force model. The reliability of the proposed procedure is verified through relevant comparisons between crack growth calculations and experimental data.

2. FATIGUE CRACK GROWTH

The integrity of engineering components is often threatened under cyclic loadings. Fatigue failures of components, can be avoided by the development of a reliable computational models/procedures for the crack growth analysis. The residual strength can be investigated through adequate crack growth laws in order to estimate the number of loading cycles up to failure. In general, crack growth problems can be considered either in one direction (through-the-thickness crack) or in two directions (surface cracks). The semi-circular crack front in a round bar, as a surface problem, requires considering two different relationships for crack growth rates, so the crack growth law proposed by Walker [4] can be expressed in the following way:

$$\frac{da}{dN}=\frac{C_A\left(\Delta K_{IA}(a,b)\right)^{m_A}}{1-R} \quad \text{and} \quad \frac{da}{dN}=\frac{C_A\left(\Delta K_{IA}(a,b)\right)^{m_A}}{1-R} \qquad (1a\text{-}b)$$

where R is the stress ratio, ΔK_{IA} and ΔK_{IB} are the stress intensity factor ranges for depth position A and surface position B, respectively. Constants C_A, C_B, m_A and m_B present material parameters experimentally obtained.

In the failure analysis, the final number of loading cycles can be calculate by integrating crack growth rate for both directions (Eqs.(1a)-(1b)) as follows:

- for depth direction:

$$N=\int_{a_0}^{a_f}\frac{da}{C_A\left(\Delta K_{IA}(a,b)\right)^{m_A}}, \qquad (2a)$$

- for surface direction:

$$N=\int_{b_0}^{b_f}\frac{(1-R)\,db}{C_B\left(\Delta K_{IB}(a,b)\right)^{m_B}}. \qquad (2b)$$

where a_0, b_0 and a_f, b_f denote initial and final crack length in depth and surface directions, respectively.

The relationships for stress intensity factor are complex, so in order to estimate residual fatigue life, adequate numerical methods have to be used for integration of complex functions.

3. STRESS INTENSITY FACTOR CALCULATION OF A THREADED ROUND BAR WITH SEMI-CIRCULAR SURFACE CRACK

The complex crack propagation process demands the inclusion of adequate parameters related to external loading, geometry and material of the structural components. Within the context of fracture mechanics, these parameters can be theoretically investigated through the stress intensity factor [12-14]. Since the semi-circular surface crack in a threaded round bar (Fig.1) is considered here, such fracture parameter can be written as follows [15]:

$$\Delta K_I = M_m\,\Delta S\sqrt{\pi a}\,, \qquad (3)$$

where ΔS is the stress range, a presents the crack length in depth direction and the correction factor M_m can be expressed on the following way:

$$M_m=\lambda_0+\lambda_1\left(\frac{a}{2r}\right)+\lambda_2\left(\frac{a}{2r}\right)^2 \qquad (4)$$

where λ_0, λ_1, λ_2 are correction factors depending of the crack length in depth a and the crack length in surface direction b, and they can be calculated by the following relationships:

for the deepest point at the crack front

$$\lambda_0=1.015-0.237\left(\frac{a}{b}\right);\ \lambda_1=-0.584+0.015\left(\frac{a}{b}\right);\ \lambda_2=6.455-3.348\left(\frac{a}{b}\right) \qquad (5a\text{-}c)$$

for the point of intersection of the crack with the free surface

$$\lambda_0=0.469+0.822\left(\frac{a}{b}\right);\lambda_1=0.377-1.478\left(\frac{a}{b}\right);\ \lambda_2=-0.160+2.946\left(\frac{a}{b}\right) \qquad (6a\text{-}c)$$

4. NUMERICAL RESULTS

Now, the validity of the proposed computational procedure for strength analysis is investigated through a few numerical examples. In such examples, both the stress analysis and the fatigue life calculation are considered.

Example 4.1. Fatigue life evaluation of the threaded round bar with surface crack

In this section, the strength of threaded round bar with semi-circular surface crack (Fig.1) is carried out. The considered round bar, made of Ti-6Al-4VAlloy, is subjected to axial loading with constant amplitude (a far field maximum gross stress S_{max}=216.51 MPa, R=0.1). Geometry and material parameters are as follows: a_0=3.01 mm, a_f=5.23 mm, 2r=19.81 mm, $C_A=1x10^{-10}$, $C_B=1x10^{-10}$, $m_A=m_B$=2.33

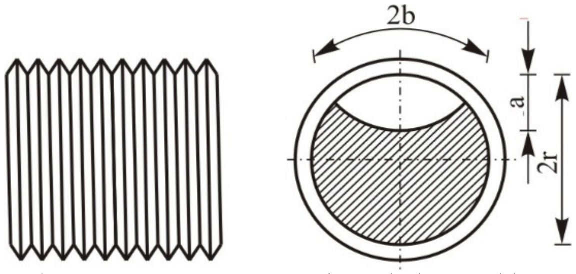
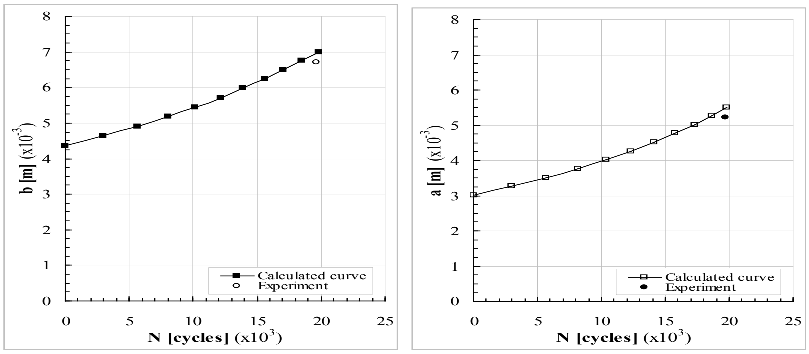


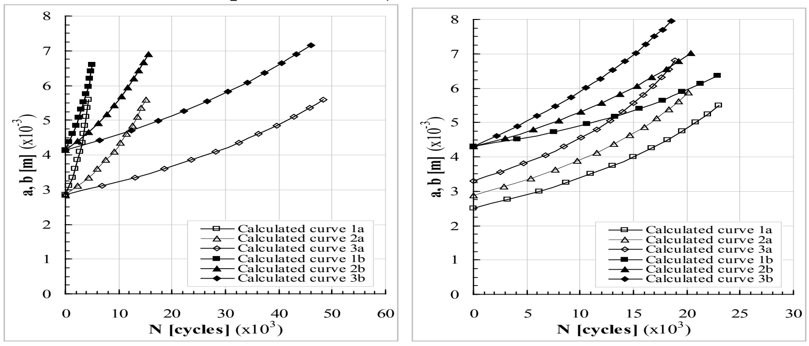
Figure 1. Geometry of a threaded round bar with semi-circular surface crack.

The fatigue failure analysis is here investigated through the stress intensity factor calculation by using Eqs.(3)-(6). Moreover, the number of loading cycles up to failure is calculated by employing Eq.(2a) and Eq.(2b) together with Eqs.(3)-(6). The computed values of number of loading cycles up to failure against crack length in depth direction and crack length in surface direction are shown in Figure 2.a and Figure 2.b, respectively. At the same Figures, all computed results for number of loading cycles up to failure are compared with experimental data.Fig.2.a and Fig.2.b show that the estimations related to the threaded round bar with semi-circular surface crack are in a good correlation with experimental observations.



(a) (b)

Figure 2. Crack length versus number of loading cycles. (a) Depth direction, (b) Surface direction)



(a) (b)

Figure 3. Crack length versus number of loading cycles (a- Depth direction, b-Surface direction)

Example 4.2. The effect of diameter and initial crack length on the residual strength of a threaded round bar under cyclic loading.

This example considers the fatigue life estimation of the threaded round bar in order to investigate the effect of diameter and crack length in depth direction on the final number of loading cycles. The threaded round bar with semi-circular surface crack (Fig.1) is subjected to tensile loading (R = 0.1). The fatigue strength calculation is performed for three different diameters (14 mm, 17.5 mm and 21.87 mm) and then for three different initial crack lengths in depth direction (2.50 mm, 2.87 mm and 3.31 mm). The threaded round bar examined here, is made of the same material as in the previous one. Using the above mentioned parameters related to geometry, loading and material of the threaded round bar, the stress intensity factor and the fatigue life up to failure can be computed by applying Eq.(2a) and Eq.(2b) together with Eqs.(3)-(6). Figures 3.a and 3.b represent the computed number of loading cycles up to failure against crack length for different values of diameter and initial crack length in depth direction, respectively:

a. Different diameter of the threaded round bar: 1 – D = 14 mm, 2 – D = 17.50 mm, 3 – D = 21.87 mm; P_{max}= 60000 N;
b. Different initial crack length in depth direction:1 – a_0 = 2.50 mm, 2 – a_0 = 2.87 mm, 3 – a_0 = 3.31 mm, P_{max}= 57000 N, D = 18 mm;

From Figures 3.a and 3.b, it can be deduced that diameter and initial length of crack in depth direction have significant impact on the residual strength of the threaded round bar with semi-circular surface crack.

5. CONCLUSIONS

The paper presents a computational model for the crack growth analysis of the threaded round bar subjected to axial cyclic loading. The theoretical investigation examines the stress analysis and the fatigue life estimation. In order to simulate the residual strength, a two-parameter driving force crack growth model is employed. A good correlation between computed results and experimental data shows that presented crack growth model is applicable in engineering practice for the reliable strength simulation of the threaded round bar with surface crack.

ACKNOWLEDGMENT

This research work has been carried out with the support of the Mathematical Institute of the Serbian Academy of Sciences and Arts and the Ministry of Science and Technological Development, Serbia under Grant No. OI 174001.

Note: This paper is based on the paper presented at The 12th International Conference on Accomplishments in Electrical and Mechanical Engineering and Information Technology – DEMI 2015, organized by the University of Banja Luka, Faculty of Mechanical Engineering and Faculty of Electrical Engineering, in Banja Luka, BOSNIA & HERZEGOVINA (29th – 30th of May, 2015), referred here as[16].

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