Crack Growth in a High Loaded Bolted Bar Connection

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ABSTRACT. *The fatigue and fracture behaviour of high loaded bolted bar connection made of high strength steel S1100Q is presented. The material parameters for the fatigue crack initiation σ_f', ε_f', b and c are determined using low cycle fatigue test according to ASTM E 606 standard. The fracture mechanics parameters (the coefficient of Paris equation C and m) are determined according to ASTM E 647 standard. Based on low cycle fatigue parameters the computational analysis is performed to determine the number of stress cycles required for the fatigue crack initiation. The remain service life up to the final failure is than determined using the known parameters C and m and calculated stress intensity factor, where 3D numerical analysis is performed. The bolted bars are also experimentally tested. Comparison of computational and experimental results shows a reasonable agreement.*

INTRODUCTION

Concerning the design of cyclic loaded engineering structures and components, the prediction of their service life is of a great importance. However, the complete service life may be divided into the following stages: (1) microcrack nucleation; (2) short crack growth; (3) long crack growth; and (4) occurrence of final failure. In engineering applications the first two stages are usually termed as "*crack initiation period*", while long crack growth is termed as "*crack propagation period*" [1]. The complete service life can than be determined from the number of stress cycles N_i required for the fatigue crack initiation and the number of stress cycles N_p required for a crack to propagate up to final failure: $N = N_\mathrm{i} + N_\mathrm{p}$.

The service life calculation of a cyclic loaded component is based on knowledge of the stresses or deformations in critical cross sections, usually calculated by means of the finite element analysis (FEA) or measured using appropriate measuring instruments. The main parameters influencing the fatigue life are the external loads and the strength behaviour of the material. Therefore, the appropriate fatigue properties of the material should be known for such analysis.

The strain-based approach to fatigue problems is widely used at present. The most common application of the strain-based approach is in fatigue of notched members. A reasonable expected fatigue life (number of stress cycles N_i), based on the nucleation or formation of small macrocracks, can be determined iteratively using Coffin-Manson equation [1, 2]:

$$\varepsilon_a = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\sigma_f'}{E} \cdot (2 \cdot N_i)^b + \varepsilon_f' \cdot (2 \cdot N_i)^c \tag{1}$$

where ε_a is the total strain amplitude, E is the modulus of elasticity, σ_f' is the fatigue strength coefficient, b is the fatigue strength exponent, ε_f' is the fatigue ductility coefficient and c is the fatigue ductility exponent. Strain-life fatigue properties σ_f', b, ε_f' and c are obtained experimentally according to ASTM E 606 standard. When the total strain amplitude ε_a in real machine part or structure is known (ε_a can be measured or determined numerically), the number of stress cycles N_i can be calculated iteratively using eq. (1).

The initiation phase of fatigue life in a virgin material is often assumed to constitute the growth of short cracks up to the size a_{th}, which is the transition length of short cracks into long cracks and may be estimated as [3]:

$$a_{\text{th}} \approx \frac{1}{\pi}\left(\frac{\Delta K_{\text{th}}}{\Delta\sigma_{\text{FL}}}\right)^2 \tag{2}$$

where ΔK_{th} is the threshold stress intensity range and $\Delta\sigma_{\text{FL}}$ is the fatigue limit of the material. However, a wider range of values have been selected for a_{th}, usually between 0.1 and 1 mm for steels where the high strength steels take the smallest values [3].

In presented work, the simple LEFM theory [4] is used to describe the fatigue crack growth from the initial (a_{th}) to the critical (a_{cr}) crack length. The appropriate number of stress cycles N_{p} is then:

$$\int_0^{N_p} \mathrm{d}N = \frac{1}{C} \cdot \int_{a_{\text{th}}}^{a_{\text{cr}}} \frac{\mathrm{d}a}{\Delta K^m} \tag{3}$$

where ΔK is the stress intensity range ($\Delta K = K_{\text{max}} - K_{\text{min}}$), which is for real machine parts or structures usually determined numerically using appropriate numerical code. In eq. (3), C and m are the material parameters, which can be determined experimentally, usually by means of a three point bending specimens according to ASTM E 647 standard.

The main purpose of the paper is to determine the low cycle fatigue parameters σ_f', ε_f', b and c (for the fatigue crack initiation) and material parameters C and m (for the fatigue crack growth) of high strength steel S1100Q, which are needed for determination of service life of machine parts and structures made of this material. Furthermore, the fatigue assessment of steel bars made of S1100Q is presented in the paper.

MATERIAL PROPERTIES OF HIGH STRENGTH STEEL S1100Q

Table 1 shows the chemical composition of the material, which was supplied as hot-rolled plates. The test specimens were cut out of the plate in the rolling direction and final machined as described in the following sections.

Table 1. Chemical composition of high strength steel S1100Q

El.	C	Si	Mn	P	S	Cr	Ni	Mo	V	Cu	Al	Nb	N	B
%	0.18	0.2	0.83	0.007	0.003	0.56	1.88	0.564	0.057	0.01	0.61	0.017	0.006	0.002

Low Cycle Fatigue Parameters

Fig. 1 shows the test specimen for determination of load cycle fatigue parameters according to ASTM E 606 standard. Before fatigue tests, the monotonic tensile test has been done using the same specimen as shown in Fig. 1, where the ultimate tensile strength R_m = 1450 MPa, the yield stress R_e = 1148 MPa and the modulus of elasticity E = 194889 MPa have been recorded.

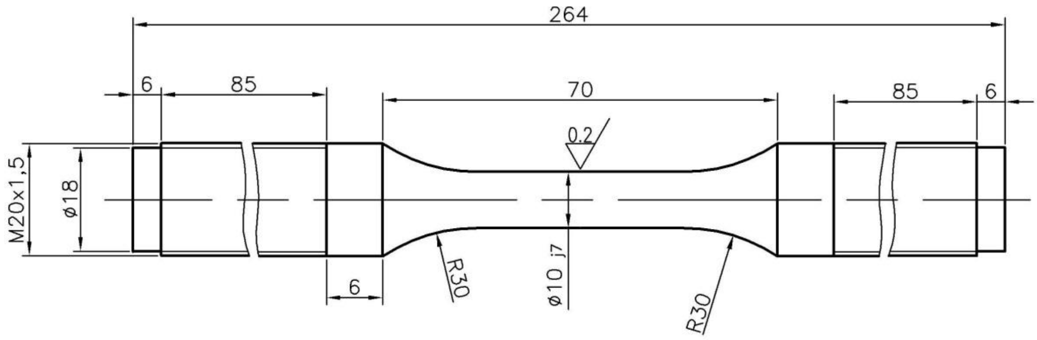

Figure 1. Test specimen according to ASTM E 606 standard

The low-cycle fatigue tests were carried out in strain-controlled regime on a servo-hydraulic fatigue machine Instron 1255 with computer aided control unit and data recording system Instron 8500. The loading waveform was triangular with loading ratio $R = -1$. The specimen temperature was 20°C and was manually checked during the test procedure using a digital thermometer. Loading frequency was higher for specimens with lower deformation amplitude as energy generated in each cycle is lower. Low-cycle fatigue parameters have been determined using the results of 8 specimens, where specimen separation has been chosen as failure criteria.

Fig. 2 shows the strain-life fatigue curves plotted in log-log scales, where N is the number of cycles to failure for each tested specimen. If the magnitudes on Fig. 2 are compared with theoretical ones in ASTM E 606 standard, the low-cycle fatigue parameters for high strength steel S1100Q result in:

σ_f' = 2076 MPa, $b = -0.0997$, $\varepsilon_f' = 9.93$, $c = -0.978$

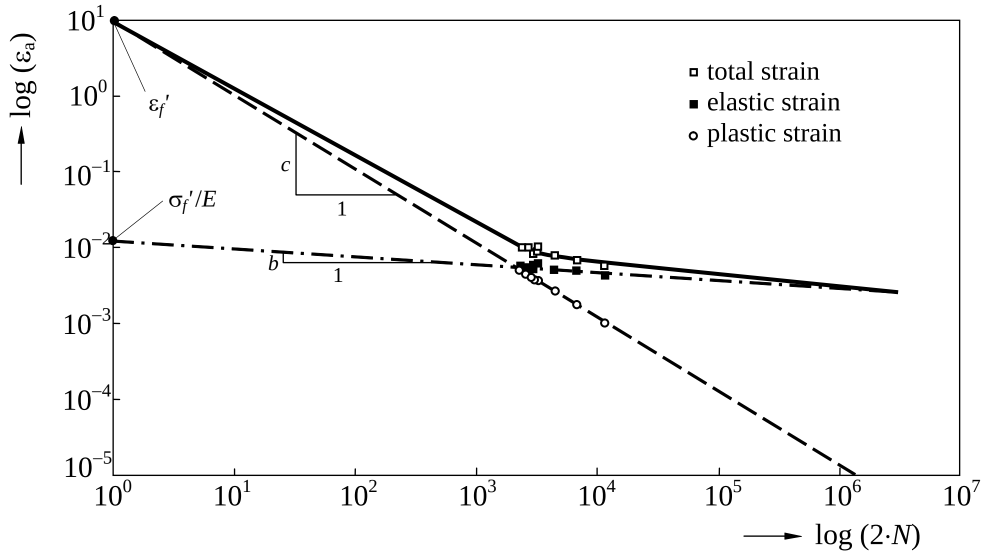

Figure 2. Strain-life curves of high strength steel S1100Q

Fracture Mechanics Parameters

The determination of the fracture mechanics parameters C and m have been determined according to standardised procedure ASTM E 647 using three point bending specimen shown in Fig. 3.

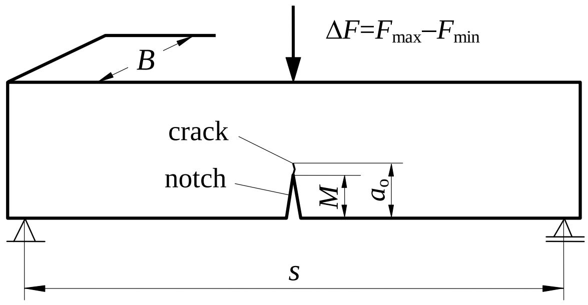

Figure 3. Three point bending specimen

Using the standard procedure ASTM E 647 the test specimens are subjected to cyclic loading and the crack propagation is measured in relation to the number of loading cycles N. That way the experimental relationship between a and N is determined and approximated with the appropriate function a=f(N). Assuming that the relationship ΔK=f(a) is known [5], the diagram log(da/dN)–log(ΔK) can then be easily constructed (see Fig. 4). The parameters C and m and the threshold stress intensity range ΔK_{th} result in:

$C = 2.02 \cdot 10^{-11}$ mm/(cycl·MPa√mm)

$m = 2.761$

$\Delta K_{th} = 315$ MPa·√mm

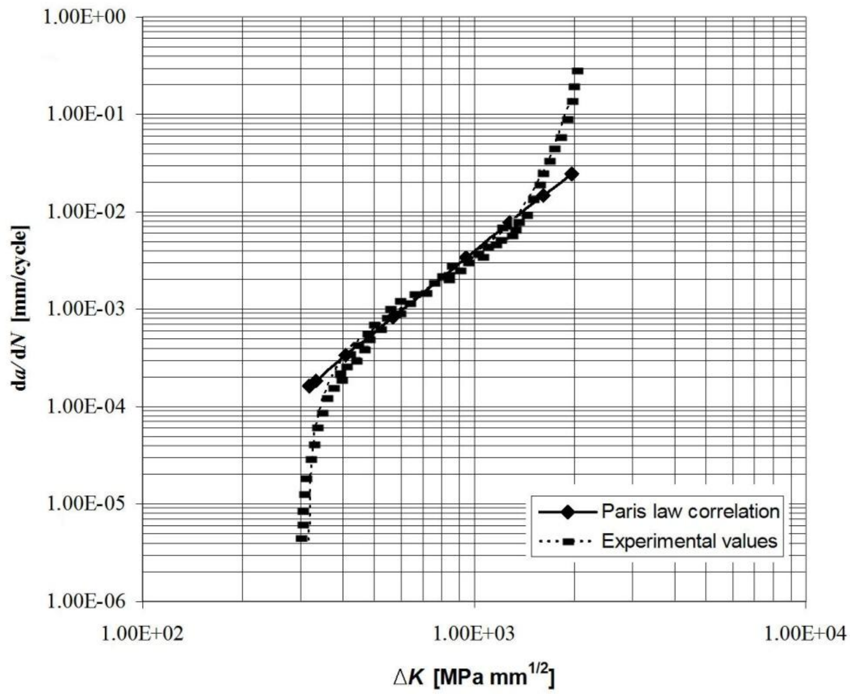

Figure 4. The diagram logΔK – log(da/dN)

PRACTICAL EXAMPLE

Crawler cranes are devices in which counter weight is usually supported by steel chain, which consists of series of high loaded bars usually made of high strength steels like S1100Q [6]. On the basis of determined material parameters, the fatigue assessment of such steel bars is analysed using experimental testing and computational analysis as described in the following sections.

Experimental testing

The fatigue tests were carried out in specially designed testing machine made of two basic rigid plates, which are connected with a central lattice (Fig. 5*a*). Load is applied using the oil pressure pumped into hydraulic cylinders, which are mounted on the basic plate. The oil pressure provides a simple means of measuring the force applied. Changing the direction of the load is done by reversing the oil flow by electrical command. The machine enables testing four bars simultaneously, with 1000 kN maximum tensile force in each bar. Actual stresses were controlled by means of oil pressure and checked by strain gauges. The testing bar (Fig. 5*b*) has a rectangular cross section (30×50 mm). Each side of the bar consists of head with the hole for the bolt. Fabrication of approximately 6 m long bars was carried out under normal production procedure (gas cutting). Grinding was done on gas-cut surfaces. The bars were loaded in tension so that the nominal applied stress was controlled in the critical cross section.

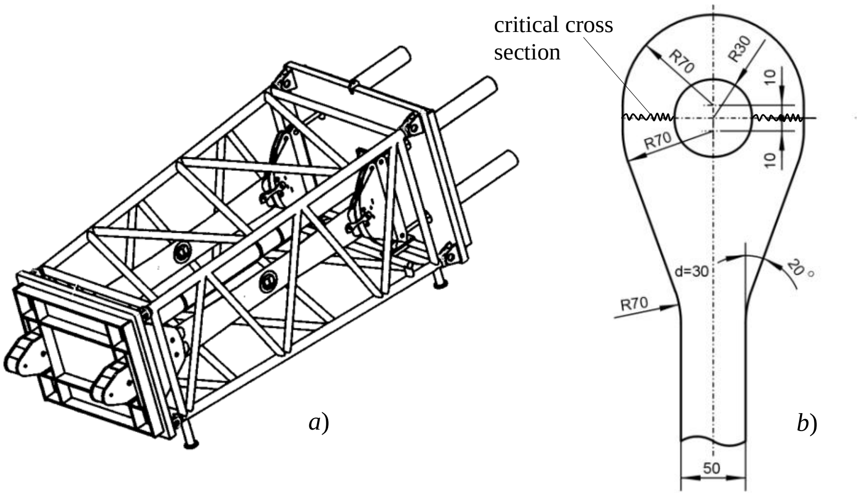

Figure 5. Fatigue testing machine (*a*) and testing bar (*b*)

Computational Analysis

A stress and deformation field in the critical cross section of the bar has been determined numerically using FEM-program code Abaqus [7]. The FE-model shown in Fig. 6*a* and loading pattern shown in Fig. 6*c* have been used in computational analysis. In the next steep, the fatigue analysis has been performed using FE-Safe program code [8]. The fatigue analysis is based on strain-life method (ε-*N*), where Coffin-Manson relationship with Morrow mean stress correction is used to determine the number of stress cycles N_i required for the fatigue crack initiation [9]:

$$\frac{\Delta\varepsilon}{2} = \frac{(\sigma_f' - \sigma_m)}{E}\left(2N_f\right)^b + \varepsilon_f' \cdot (2N_f)^c \qquad (4)$$

where Δε is the true strain range, σ_m is the mean stress and *E*, σ_f', ε_f', *b* and *c* are material parameters described in previous sections.

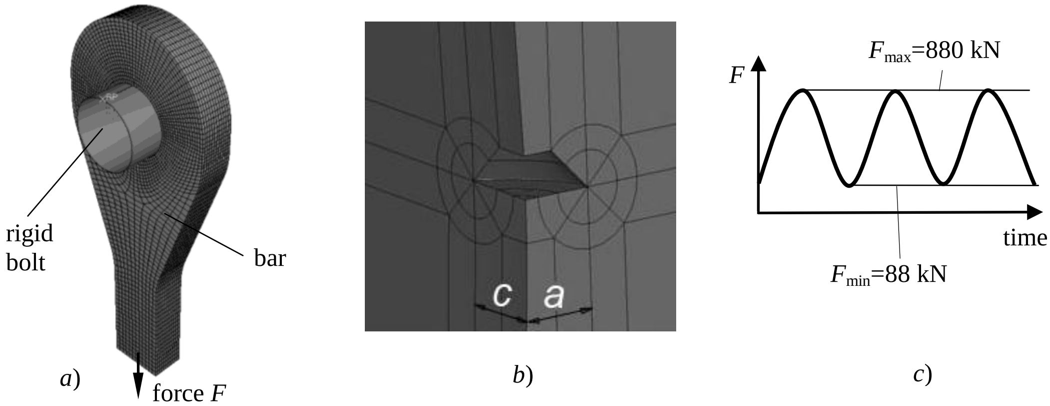

Figure 6. Numerical model (*a*), initial crack (*b*) and loading pattern (*c*)

The numerical model for the fatigue crack growth consists of the geometry with a modeled crack in the region where a crack was being observed in experimental test bars. The initial crack is modeled as a quarter elliptical edge crack with main ellipse axis *c* along the hole surface and *a* along the face of the lug (Fig. 6*b*). The initial crack length $a = c = 0.2$ mm has been determined using eq. (2) with consideration of previously determined threshold stress intensity range $\Delta K_{th} = 315$ MPa·√mm and fatigue limit $\sigma_{FL} = 390$ MPa [10].

In numerical simulation, the stress intensity factors were determined for different sizes of the crack. The obtained results were then used for derivation of the correction function f_a and f_b to be used with standard model, which assumes the plate with quarter elliptical edge crack, loaded in tension and bending [11]:

$$f_a = 1{,}4583 \cdot 10^{-6} a^3 - 2{,}0501 \cdot 10^{-4} a^2 - 1{,}4278 \cdot 10^{-2} a + 1{,}1254 \quad (5)$$

$$f_c = -4{,}08 \cdot 10^{-4} c^2 - 3{,}035 \cdot 10^{-3} c + 9{,}7322 \cdot 10^{-1} \quad (6)$$

The scale functions f_a in f_c have then been used to determine the stress intensity range ΔK using analytical procedure as described in [11]. The crack growth has then been analyzed with eq. (3) using material parameters *C* and *m* as described in previous sections. The numerical analysis was stopped when the stress intensity factor reached its critical value $K_{Ic} = 2100$ MPa·√mm (Fig. 7).

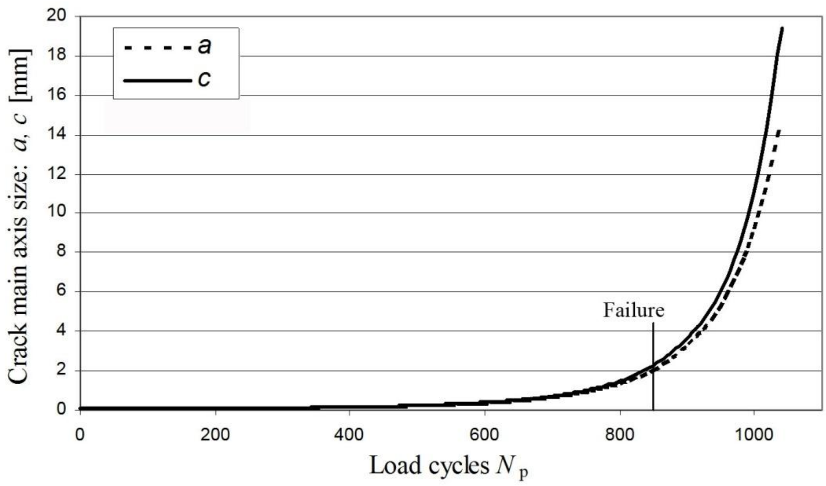

Figure 7. Numerical analysis of the fatigue crack growth

Experimental and computational results

Figure 8*a* shows the fatigue breakage of the tested bar. The fatigue crack was initiated at the edge of the hole, which can be shown from Fig. 8*b*. The initial crack then propagates until the final fracture in the critical cross section. The number of stress cycles required for the fatigue crack initiation N_i and fatigue crack propagation N_p determined using presented computational model is shown in Table 2.

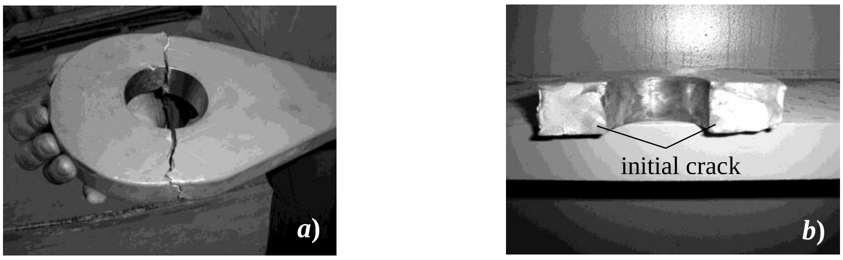

Figure 8. Fatigue breakage of testing bar (*a*) and example of fracture surface (*b*)

Table 2. The number of stress cycles N required for final failure ($N = N_i + N_p$)

Experimental results				Computational results		
Test 1	Test 2	Test 3	Test 4	N_i	N_p	N
38029	26727	24795	29036	28705	845	29550

CONCLUSION

The experimental determination of fatigue and fracture mechanics parameters of high strength steel S1100Q is presented. The low cycle fatigue parameters σ_f' = 2076 MPa, b= –0,0997, ε_f' = 9,93 and c = –0,978 are determined following the standard procedure ASTM E 606. On the basis of this parameter the fatigue initiation period N_i can be determined. In the second part of the paper, the complete procedure for determination of the coefficients $C = 2.02\cdot10^{-11}$ mm/(cycl·MPa√mm) and m = 2,761 for treated material is presented. On the basis of these parameters, the crack propagation period N_p can be determined. The proposed computational model is used to determine the service life of a counterweight bolted bar connection.

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