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Nominal Stress-Based Estimation of Fatigue Life of Welded Joints

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Abstract: The paper presents methods for determining the fatigue life of welded joints with particular emphasis given to typical joints. In addition, the article presents various possible nominal stress-based ways enabling the calculation of stresses, including structural stresses and involving the most complex linear fracture mechanics. The paper also discusses recommendations by the International Institute of Welding related to the determination of the fatigue life of welded joints in flat elements exposed to tension-compression conditions. The work is focused on assessing the fatigue life of welded joints (selected types) in accordance with the guidelines specified in related recommendations issued by the International Institute of Welding and taking into consideration the analysis concerned with the safety of such structures.

Keywords: fatigue service life, welded joint, fracture mechanics, effective stress, nominal stress

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Introduction

Over the past 30 years, the issue of calculating fatigue service life has been thoroughly discussed in numerous studies and publications [1]. In terms of welded joints, the radius of the welding notch frequently approaches zero, consequently producing stresses approaching infinity. As a result, it is not possible to refer to actual stresses in welded joints. It is only possible to refer to "some" computational stresses or to apply fracture mechanics typical of cracks having radiuses approaching zero [2, 3].

According to publication [4], there are two principal approaches concerned with the determination of computational stresses aimed to identify the fatigue service life of welded joints, i.e. an approach based on nominal stresses and an approach based on strictly local stresses determined at a special crack initiation spot (also referred to as "hot spot").

Publication [5] refers to the "hot spot" method by Haibach and Hamad and R = 1 mm radius method. In turn, J. Martinsson [6] refers to four methods, i.e. related to nominal stresses, structural stresses, effective stresses and stresses obtained on the basis of linear fracture mechanics.

The nominal stress-based analysis is recommended where an element subjected to analysis is one of classified elements and where stresses are easy to determine. In work [7], L.

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Susmel and R. Tovo performed numerous nominal stress and constant amplitude load-related calculations concerning welded joints.

The so-called "hot spot" method is recommended if, in relation to a prototype, it is possible to measure a distortion near the joint [4, 8] or if the distortion can be calculated using the Finite Element Method (FEM). In work [8], K. Van Dang et al., when performing fatigue tests of steels, observed (on the basis of stresses determined using the "hot spot" method [9, 10] that the fatigue service life of welded joints was little dependent on types of materials being joined.

The use of the local approach to welded joints requires knowledge related to the concentration of tensile, bending and torsional stresses at the edge of the penetration [11]. However, because it is usually impossible to measure the actual radius of the penetration edge, it is necessary to apply a method capable of addressing this issue. The above-presented problem was solved successfully by introducing the notion of the so-called fictive or conventional radius [12, 13], based in the Neuber theory [14]. In practice, in cases of welded joints made in steel, a fictive radius is modelled at the bottom of the notch (ρf = 1 mm). The aforesaid method is applicable in relation to the tension of flat elements having thicknesses not exceeding 5 mm.

A method similar to that proposed by H. Neuber (based on the fictive radius at the bottom of the notch) was proposed by F. W. Lawrence et al [15]. This model involves the determination of the maximum value of stress concentration fatigue factor Kfmax. The aforesaid value is determined in relation to the critical radius at the end of the notch, equal to the critical value dependent of a given material. The value is restricted within the range of approximately 0.1 mm (in relation to welds made of high-alloy steels) to 0.25 mmm (in relation to welds made of low-alloy steels).

Another method enabling the determination of geometrical stresses, subsequently used in calculations concerning fatigue service life, was proposed by Z. G. Xiao and K. Yamada [16] who suggested that calculations should involve stresses present 1 mm away from the interface of joined materials (on their surface).

Selected recommendations based on nominal stresses

As can be seen, the above-presented methods only approximate actual stresses present in welds. For this reason it seems recommendable to apply the simplest methods based on nominal stresses. Typical recommendations concerning calculations related to welded joints are contained in the standards of Eurocode 3 [17].

The analysis based on nominal stresses is recommended where an element subjected to analysis is one of classified elements and where stresses are easy to determine. The aforesaid types of divisions are quite numerous [18].

Previously applied British [19], Japanese [20] or American [21] recommendations were based on the use of nominal stresses. All of these recommendations addressed to design engineers are based on the classification of individual types of welded joints according to fatigue category FAT, characterised by the constant slope of the fatigue curve. The Japanese recommendations (JSSC) contain the classification of 8 types of welded joints (A–H), whereas the American recommendations (AASHTO) specify 7 types of joints (A–E). The aforesaid recommendations are concerned with characteristics having a parallel slope and factor m = 3. In terms of JSSC, the x-axis represents the range of normal nominal stresses. As regards AASHTO, the aforesaid range is concerned with nominal tangent stresses. The British standards contain the classification of 9 types of welded joints.

The proposal contained in the guidelines formulated by the International Institute of Welding (IIW) [22] is a simplified method (similar to other methods, also based on a simplified approach). An interesting aspect is to what extent simple recommendations by IIW enable the design of safe and cost-effective welded structures. The aforesaid recommendations include 13 fatigue categories. The development of IIW recommendations [22] was supervised by A. Hobbacher. The assumptions of the aforesaid recommendations were presented by the author in publication [21] and popularised in publications [23, 24] (following the issue of the recommendations). As mentioned in the Introduction, the recommendations suggest the creation of various fatigue categories (FAT) related to specific types of welded joints. Such an approach only requires the use of nominal stresses. Individual fatigue categories have been assigned to individually classified welded joints. A given fatigue category specifies the range of stresses $\Delta\sigma$ = FAT in relation to fatigue service life Nf = 2·106 cycles. Appropriate fatigue characteristics have slope m = 3 within range Nf (104, 107) cycles. In terms of higher number of cycles than 107 (cycles), a horizontal line is assumed for standard applications of welded joints. In relation to a very high number of cycles, slope m = 22 is assumed. All diagrams are limited from above by fatigue category FAT = 160 in relation to steel welded joints and slope m =5. The aforesaid characteristics were created for rolled or extruded elements, elements with edges subjected to treatment and seamless hollow elements. In relation to the proposal formulated by Basquin, fatigue service life within the range of 104 – 107 cycles can be determined using the following formula

$$N_f = \left(\frac{\mathrm{FAT}}{\Delta\sigma}\right)^m \cdot 2 \cdot 10^6 = \left(\frac{\mathrm{FAT}}{2\sigma_{an}}\right)^m \cdot 2 \cdot 10^6$$

Such an approach when using the IIW recommendations implies that 97.7 % of welded joints subjected to tests will withstand previously assumed fatigue service life. As regards the base material or full penetration in a butt joint, it is recommended to apply fatigue category 100 for steels and fillet welds. In turn, in terms of the incomplete penetration of butt welds it is recommended to use FAT 80.

Experimental tests

The tests involved three types of welded joints, i.e. flat butt joints with the weld face not subjected to treatment – (fatigue category) FAT 90, joints with a transverse rib – FAT 71 and butt joints made of round specimens with the weld face subjected to treatment – FAT 112. The tests and analysis are presented on the basis of tests performed by C. M. Sonsino [25]. The tests were performed in relation to a constant amplitude load characterised by stress ratio R. First, the tests involved the joints subjected to the symmetric cycle where R = -1. Afterwards, the tests were performed using the off-zero pulsing cycle where R = 0. Next, the tests involved the cylindrical specimens where both the weld face and weld root had been subjected to treatment. The above-named case involved the application of the symmetric load where R = -1. The tests of the joints with a transverse rib were performed using a similar scheme to that applied in relation to the butt joints where the weld face had not been subjected to treatment.

The fatigue tests involved specimens made of four different materials. The static properties of the materials are presented in Table 1.

Table 1. Static properties of test steels [25, 26]

Steel	E, GPa	R_m, MPa	$R_{0,2}$, MPa
S355N	206	560	378
S355M	206	524	422
S690Q	206	868	784
S960Q	206	1072	998

Comparison of test results with fatigue categories (FAT)

The presented test results and fatigue characteristics developed on the basis of the tests in accordance with recommendations specified the ASTM standard [27] are related to three individual types of welded joints made of four types of materials. The aforesaid experimental test results are confronted with determined fatigue categories (FAT). The comparison of the test results and fatigue categories (FAT) is

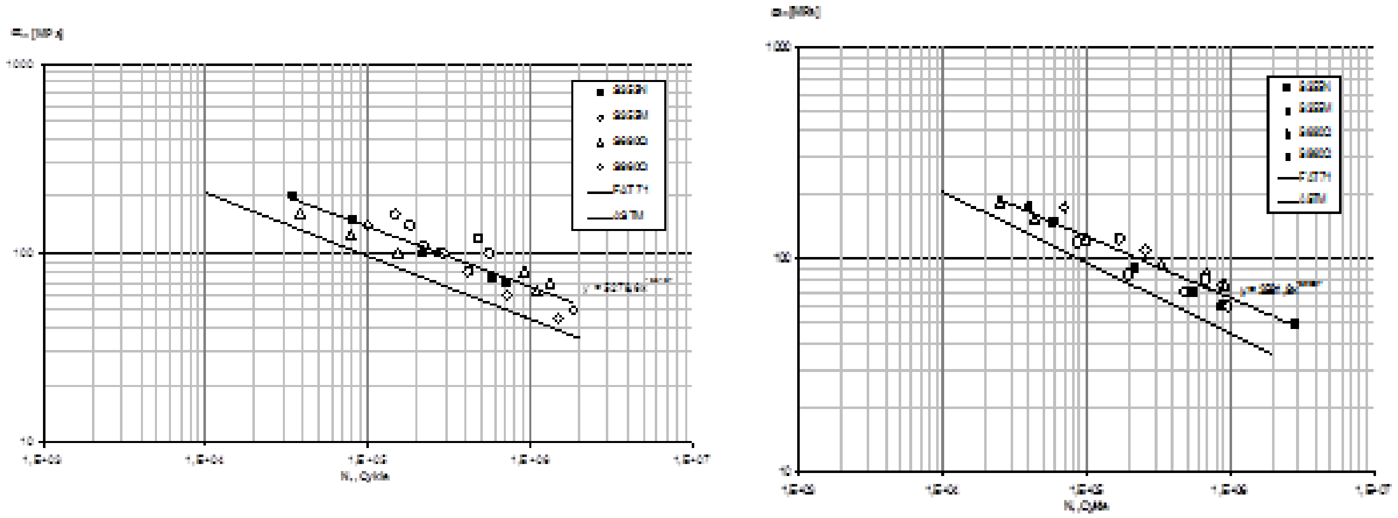

Fig. 1. Comparison of the fatigue test results concerning the K-type joints with the transverse rib and fatigue characteristic FAT 71 in relation to the symmetric cycle-based load: a) R = -1, b) R = 0

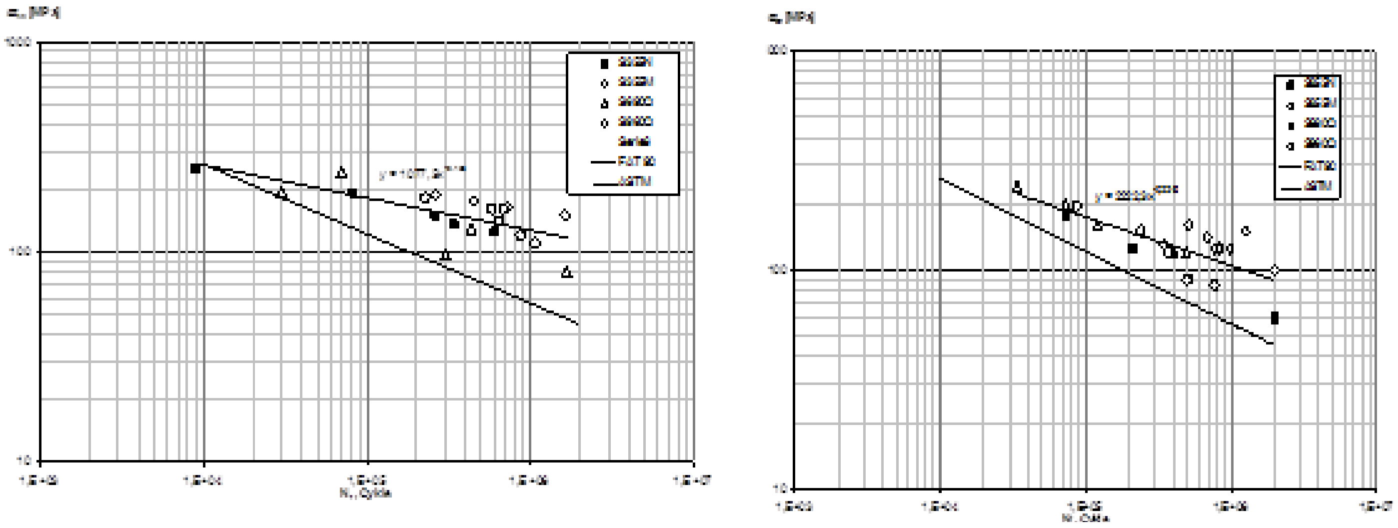

Fig. 2. Comparison of the fatigue test results concerning the X-type butt joints and fatigue characteristic FAT 90 in relation to the symmetric cycle-based load: a) R = -1, b) R = 0

presented in Figures 1–3. The aforesaid Figures present the fatigue characteristics FAT in relation to a given welded joint type, points with experimental test results and the fatigue characteristics obtained on the basis of the aforesaid points and best matching experimental tests in accordance with characteristics (1). On the basis of the obtained results it can be stated that fatigue characteristics FAT are always on the safe side; an exception being fatigue category FAT 90 in relation to the symmetric load. In addition, the fatigue characteristic FAT is not parallel to that obtained on the basis of the experimental test results. Fatigue characteristics FAT 112 of the welded joints is not parallel to that obtained as a result of the experimental tests. The above-presented calculations lead to a situation where the operation of the structure will be characterised

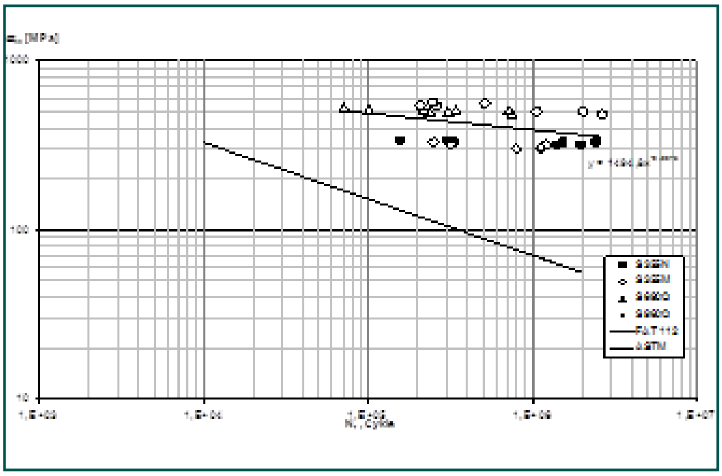

Fig. 3. Comparison of the fatigue test results concerning the X-type butt joints and fatigue characteristic FAT 112

by relatively low effort, which, in turn, leads to the conclusion that the FAT-based calculation results are excessively conservative.

Conclusions

The analysis of the obtained test results justified the formulation of the following conclusions:

1. In relation to K-type crosswise welded joints, the design of safe structures taking into consideration fatigue characteristic FAT 71 (in accordance with IIW recommendations) provides positive results nearly within the entire range of fatigue service life.
2. In relation to X-type butt welded joints, the design of safe structures taking into consideration fatigue characteristic FAT 90 (in accordance with IIW recommendations) provides positive results only in relation to a number of cycles exceeding 100 000.
3. In relation to X-type butt welded joints, where the weld geometry is subjected to treatment as the geometry of the base material, the design of safe structures taking into consideration fatigue characteristic FAT 112 (in accordance with IIW recommendations) provides positive results in relation to both higher and lower numbers of cycles.
4. The assumption that 97.7% of joints would withstand a previously adopted number of cycles was fulfilled.
5. Stress ratio R had a very low impact on fatigue service life in relation to the fatigue test results subjected to analysis.
6. The fatigue service life does not depend on materials being joined but solely on the type of a welded joint.

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