

## INCREASING THE CYCLIC STRENGTH OF THREADED JOINTS THROUGH THE UNLOADING OF CRACKED SECTIONS

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*(Received 05 December 2011; accepted 04 June 2012)*

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### *Abstract*

*The cyclic strength of the axially loaded threaded joints is considered and the procedural method to increase their lifetime through the unloading of cracked sections is presented. The method operates by varying the mutual positions of the stud and the nut. It was shown how to exploit resources of the threaded joint after opening of the crack without reduction of the safety. The developed mathematical model allows control the accumulation of the fatigue damage as well as the crack growth in the roots of the stud thread. Increase of the cyclic lifetime is theoretically evaluated by the ratio of the numbers of loading cycles required to initiate cracks in the roots of unengaged and the most dangerous engaged turns of the stud. Performance of the elaborated technique is demonstrated by considering the crack growth in depth of the nut. The relative safety of the unloaded cross-sections containing cracks is studied. Comparison of the presented developments with standard safety requirements is presented.*

*Keywords: Threaded joints; Fatigue; Damageability; Crack*

### **1. Introduction**

Understanding of the nature of fatigue phenomena is fundamental issue continuously considered by many

researches. Nowadays, the emphasis is given towards investigation of microstructural effects, understanding of fatigue mechanisms or production of new metallic materials [1-4]. In many cases, cyclic

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strength may be critical in a reliable engineering design while fatigue damage of smaller elements can cause the failure of complex structural systems or limit the cyclic lifetime of the structure as a whole.

Performance of threaded joints under cyclic loading plays an important role in the integrity and functionality of equipment and machines explored in various industries. The fatigue behaviour of threaded joints is contributed by additional factors related to specific geometry and stress distribution. More definitely, accumulation of damage, crack initiation and further complete fatigue failure of the stud-nut joint occurs in the stud cross-section at the root of the turn engaged with the first full profile turn of the nut near its bearing surface.

There are various traditional engineering techniques reported in earlier literature [5-7] to increase fatigue life which decrease the notch effect of the thread. By applying technological measures, the decreasing of the stress concentration can be achieved by either increasing the thread root radius or applying an improved profile of the thread turns [8, 9]. In addition, roll-formed threads after heat treatment have greater fatigue strength compared to machined (turned, milled, ground) threads. The fatigue life of the threaded joint can be increased also by using microstructurally optimized bolts with graded grain size [10].

Various constructional innovations have been elaborated to improve the load distribution in threads. For example, there are nuts with tapered threads [11, 12], nuts with bevel at the loaded face [13] or stud threads with gradually reduced height in the direction of the bearing surface of the nut

[14]. Applying such nuts or bolts, the stresses in the thread roots are reduced rather effectively.

However, increasing of the cyclic lifetime of the threaded joints without increasing their sizes is still a significant challenge in engineering design. Therewith, deeper knowledge about distribution of internal forces in the joint is of major importance. Series of the first results considering the distribution of loads in the nut—bolt connection were reported in [15-17]. Here, the finite element method was employed.

Many studies on threaded connections have been performed in relation to the fatigue. A review of the earlier contributions in development of the bolt fatigue-life prediction methods is presented in review by Patterson [18]. A review of experimental method to study the fatigue behavior of bolt–nut threaded connections under a state of cyclic tensile loading is given in [19].

The capacity of joint to resist cyclic load fatigue up to the complete failure of the stud is the long time period. Two dominant stages may be distinguished. The first stage comprises accumulation of the fatigue damage, while the second stage runs from the instant of the macrocrack opening. The experimental procedure to study both of the stages of initiation and crack growth is elaborated in [19, 20]. On the basis of earlier findings, two possible sources in order to increase the lifetime of a conventional threaded joint may be considered.

It should be noticed that variation of the stresses in a conventional stud-nut joint is predicted through the combination of two loads, i.e. the locally concentrated thread loads and the axial forces of the stud core

both increasing towards the bearing surface of the nut. It is obvious that stud segment located inside of the connector is loaded only by the axial tension force. Consequently, the stress in unengaged thread within this segment is considerably smaller compared to the risky stud turn near the bearing surface of the nut [16]. In summary, the capacity of the unengaged threads to accumulate the fatigue damage over the whole operation time remains unused. The possibility to prolong the fatigue life by shifting risky stress concentration just before opening of the crack is already considered in [21, 22] where the optimal number of cycles is evaluated by solving optimisation problem.

A further resource of prolongation of the fatigue life is ability to control the fatigue behaviour after opening the crack. On the basis of conducted own experiments [20] the crack propagation stage is usually longer than the first stage of the fatigue crack initiation. It should be noticed that the macrocrack growth stage of the stud is eliminated from the design standards of the stud fatigue life due to high safety requirements of the threaded joints [23, 24]. According to this concept, the propagation of the crack is not allowable for higher safety reasons; therefore this is important resource is also unused and remains beyond the consideration.

In this article the procedural method through the unloading of the cracked sections is proposed in order to increase the cyclic lifetime of threaded joints. By changing the mutual positions of the stud and nut in a threaded joint, it is possible to exploit both above mentioned resources of the threaded joint after opening of the crack

without reduction of the safety.

The paper is organized as follows. The concept of the crack unloading method is described in Section 2. The crack initiation indexes defining the number of loading cycles required to initiate cracks in the roots of the stud turns are defined in Section 3. The performance of the elaborated technique is demonstrated in Section 4. Crack growth in depth of the nut analysis is given in Section 5, where the unloading of the crack leading to prolongation of fatigue life is clearly demonstrated. The relative safety of the unloaded cross-sections containing cracks is studied in Section 6 and the final conclusions are formulated in Section 7.

## **2. The concept and mathematical model of increasing the cyclic strength life of threaded joints**

The concept to increase the cyclic strength of threaded joints under tension is elaborated by considering the variation of the stud turns load and corresponding stresses along the symmetry axis of the joint. It is well known [5, 6] that the maximum stresses as well as the maximum accumulation rate of the cyclic damages occur in the stud turn root which is engaged with the first full-profile turn of the nut. Consequently, the stresses in the stud turn roots could be controlled by changing the position of the nut in an appropriate way.

The method to increase the cyclic strength of the threaded joints proposed here makes it possible to reduce the loading level of the damaged cross sections of the stud by varying the mutual position of stud and nut.

The cyclic strength of the threaded joint is

related to its ability to withstand accumulated fatigue under cyclic loading. The entire fatigue life of the joint is defined by the critical number of load cycles  $N_0$ . This parameter indicates the safety threshold to withstand fatigue damage of the joint. Critical damage of the joint is characterised by the initiation of the fatigue crack which occurs at the stud turns under a cyclic load.

The unloading concept of the damaged turns of the stud containing cracks is illustrated in Figure 1. Let us consider an axisymmetric cross-section of the threaded joint subjected by the cyclic tension force  $F$  as a one-dimensional problem with respect to axis  $z$ . Here, the stud is denoted by numeric symbol 1, the nut by 2 and the bush-washer by 3. The nut geometry is characterized by its height  $H$ . Technically, the unloading may be controlled by periodically decreasing the height of the bush-washer.

Evaluation of the local damage and its role for the entire fatigue life of the threaded joint is utilized by considering two specific sections  $C$  and  $A$ , respectively. Firstly, we distinguish the most risky section of the joint denoting it hereafter with  $C$ . It is well known that only in this section of the joint, the highest load occurs in the turn of the stud engaged with the first full-profile turn of the nut. Thus, the critical cyclic damage accumulation runs in the critical cross-section of the stud located in the level of the risky section  $C$  of the joint. Consequently, the entire fatigue life of the stud is related to section  $C$  and it is defined by the critical number of load cycles  $N_0=N_{0C}$ .

It is obvious that, the critical cross-section of the stud is related to the fixed relative position of the nut. It may move by shifting

the nut. The available critical sections of the joint positioned below the nut, i.e. in the area of the bush-washer, are denoted hereafter as sections  $A$ .

It is known that the local stresses which act on the unengaged turns of the stud are about two times less here than those in the level of the risky section  $C$  of the joint. Therefore, the fatigue life for the unengaged stud is expressed by the critical number of cycles  $N_{0A}$ , where  $N_{0A}>N_{0C}$ .

In light of the above approach, the number of loading cycles  $N_{0A}$  and  $N_{0C}$  until crack initiation in the roots of the stud turns, are decisive parameters characterizing the fatigue life of the threaded joint. Control of the fatigue loading is implemented in the following manner. The initial position of the nut with respect to axis  $z$  is defined by the initial height  $H_w$  of the bush-washer (Fig. 1a). Thus, the risky section of the joint denoted by  $C$  coincides with the stud root point 1\*. This means that the first cyclic loading period  $T_1$  runs until the crack initially appears in the root. During the first loading period, the total fatigue life  $N_{0C}$  however, is explored by the capacity of a single cross-section of the stud. Thus,  $T_1$  is characterised by  $N_{0C}$ .

Periodical changing of the mutual position of the stud 1 and the nut 2 is illustrated in Figs. 1b and 1c. The new positions of the nut are fixed by an incremental procedure which is implemented by a sequential reduction the height  $H_w$  of the bush-washer 3 with the height increment  $\Delta H$ . It should be noticed that the changing procedure is performed in the untighten state of the threaded joint but the threaded joint must be tight again after each new operation.

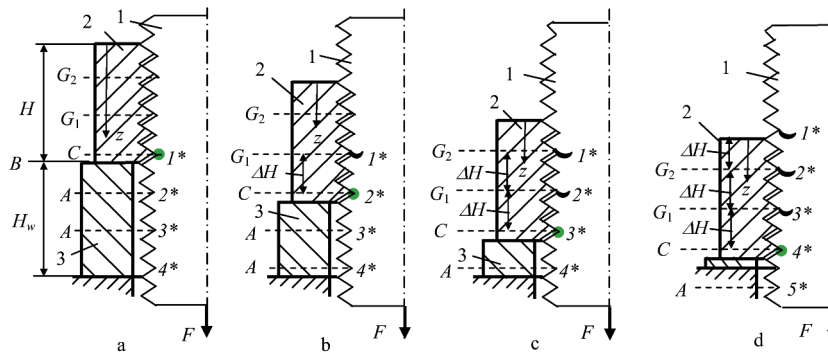


Fig. 1. Illustration of turns unloading by the sequential change of the nut positions using the bush-washer of variable height: a) initial position, b, c) intermediate positions, d) final position: 1 – stud, 2 – nut, 3 – bush-washer; ● - crack initiation, ~ - small cracks

During the first shifting, the nut is being moved by a distance of  $\Delta H$ . Consequently, the cracked turn 1\* of the stud is shifted into the depth of the nut and occurs in the level of section  $G_1$  (Fig. 1b). Therewith, the cross-section of the stud with the initial crack is unloaded and moves from critical to a safe state with a sufficiently lower load level.

Simultaneously, the damaging nut turn located in section C engages with the other, previously unengaged turn 2\* of the stud. The crack is now being formed in the root of this stud turn. The crack is initiated here after the second cyclic loading period characterised by  $T_2$  loading cycles. The third positioning period is characterised by the presence of two cracked turns of the stud with roots 1\* and 2\*. Since they are engaged with the thread of the nut in the levels  $G_1$  and  $G_2$  of the nut, the cracks growing are almost frozen. As in the previous case, the fatigue damage is accumulated in root 3\* of the stud turn engaged with the most damaging turn of the nut located in the nut section C. Here, the cross-section of the stud can withstand  $T_3$  loading cycles until the initiation of the crack.

If the height of the bush-washer is greater than the nut height, the stud cracked cross-section can occur in the unloaded position behind the free end of the nut. This case is illustrated in Fig. 1d where the stud cross-section with cracked root 1\* occurred in the unloaded position.

The unloading procedure of the cracked cross-sections of the stud when the nut is being shifted over the same distance  $\Delta H$  may be repeated several times. We denote each of the cyclic loading periods by subscript  $j$  ( $j=1, 2, \dots, u$ ), where  $u$  is the total number of loading periods. In terms of the above notation, we can shift the nut  $u-1$  times and allow for the opening of  $u$  cracks in the roots of the stud turns.

Formally, only the initial height of the bush-washer  $H_w$  predefines the total number of the cyclic loading periods upon the condition  $H_w \geq (u-1)\Delta H$ . From the point of view of the cyclic strength, shifting the nut by rotating should be stopped when cracks occur in unengaged turns left in the cavity of the bush-washer. It means that total number of the loading cycles  $T_{sum} = \sum_{j=1}^u T_j$  should remain below the critical value

$$\sum_{j=1}^u T_j \leq N_{0,A} \quad (1)$$

The above condition predefines the limit of the maximal number of loading cycles  $T_{sum,max}=N_{0,A}$ , while fatigue life could be maximally increased by  $N_{0,A}/N_{0,C}$  times.

The mathematical description of the damage accumulation is based on the relations of conventional fatigue. Let us consider the most critical cross-section  $i=1^*$  of the stud which undergoes damaging fatigue due to its turn engagement with the nut turn in the risky section  $C$  during one loading cycle. In addition, the local stress state in root of this turn during each of the loading periods is assumed to be stationary.

The damageability of cross-section  $1^*$  of the stud is characterised by a damage accumulation rate  $\kappa_C$  which may be related to the critical number of loading cycles as:

$$\kappa_C = \frac{1}{N_{0,C}} \quad (2)$$

In the initial loading period characterised by  $T_1$  cycles the damage amount accumulated in the stud section  $i=1^*$  could be evaluated as the product  $D_C=T_1 \times \kappa_C$ .

The damageability of unengaged turns of the stud positioned in sections  $A$  of the joint, i.e. below the nut in the cavity of the bush-washer, may be considered in the same manner. It is characterised by a damage accumulation rate  $\kappa_A$  which may be related to the critical number of loading cycles as:

$$\kappa_A = \frac{1}{N_{0,A}} \quad (3)$$

In the initial loading stage, the damage amount accumulated in the stud cross-section  $i > 1^*$ , i.e. in roots  $i=2^*, 3^*, \dots, u^*$ , could be evaluated as  $D_A=T_1 \times \kappa_A$ .

This approach may be utilised for the characterisation of damageability during other loading periods. Thus, the damage accumulated during the second loading period in the roots  $i > 2^*$  of the unengaged stud thread, i.e. in roots  $i=3^*, 4^*, \dots, u^*$ , could be evaluated as  $D_A=T_2 \times \kappa_A$ .

The damage accumulation behaviour of the unengaged turns going into contact with the nut after shifting is slightly different. Each of the unengaged turns  $i > 1^*$ , i.e.  $i=2^*, 3^*, \dots, u^*$ , are initially subjected by stationary cyclic load. Here, damage accumulation is described by the damageability  $\kappa_A$  while in the most risky state, it is described by  $\kappa_C$ . Transition into the most risky position  $C$  of the joint is subjected by the increase of local stresses, therefore, loading cannot be regarded as stationary. The influence of the non-stationary loading is additionally evaluated by the factor  $d_h$ .

Its value depends on the material properties [25-28]. If damage accumulation increases, thus  $d_h > 1$  and oppositely, if damage accumulation decreases, then  $d_h < 1$ . For insensitive materials,  $d_h=1$ . Finally, the damageability of the critical cross-section of the stud with regard to damage accumulation in the risky position  $C$  is corrected and defined as:

$$\kappa_{aC} = d_h \frac{1}{N_{0,C}} \quad (4)$$

Consequently, accumulated damage for each stud cross-section  $i > 1^*$  during the loading period  $j > 1$  ( $j=i$ ), is evaluated as  $D_{CA}=T_1 \times \kappa_{aC}$ .

It should be noted that position of the nut may be changed by shifting it even before reaching critical damage. An uncracked root



Expressions (7) and (9) illustrate the importance of the critical parameters  $N_{0A}$  and  $N_{0C}$ . It has been shown that an increase of the value of the relation  $N_{0A}/N_{0C}$  increases the total number of loading cycles  $T_{sum}$  keeping the frozen cracks, therewith prolonging the fatigue life of the joint defined as  $T_{sum}/N_{0C}$ . It is easy to confirm that the infinite number of positionings  $u=\infty$ , yields the limit value  $T_{sum}=N_{0A}$  as a consequence, the increase of the fatigue life is bounded by a theoretical limit equal to  $N_{0A}/N_{0C}$ .

**Model II.** Problem two is formulated in a slightly changed approach for the positioning of the nut. During the first loading period the joint is loaded in the same manner until the crack is initiated in the stud root 1\*. In order to simplify the control of loading, equal loading periods are required during the positioning. Denoting an unknown number of loading cycles by  $T_{eq}$ , the set of variables for each of the loading periods  $j$ , i.e.  $j=2, 3, \dots, u$ , is defined by a single variable  $T_{eq}$ . Consequently, by considering the constraints:

$$T_2 = T_3 = \dots = T_{u-1} = T_u = T_{eq} \quad (10)$$

The set (5) of  $u$  equations is reduced to a set of two equation with two variables  $T_1$  and  $T_{eq}$ . A detailed examination of the equations shows how the solution could be obtained by solving the first and last equations. The mathematical model (5) after its reduction into two equations became very simple. It is written as follows:

$$\begin{aligned} \kappa_c T_1 &= 1 & i &= 1^* \\ \kappa_A T_1 + (u-2)\kappa_A T_{eq} + \kappa_{ac} T_{eq} &= 1 & i &= u^* \end{aligned} \quad (11)$$

It is easy to confirm that the remaining  $u-2$  equations are transformed into strong

inequalities

$$\begin{aligned} \kappa_A T_1 + \kappa_{ac} T_2 &< 1 & i &= 2^* \\ \kappa_A T_1 + \kappa_A T_2 + \kappa_{ac} T_3 &< 1 & i &= 3^* \\ \kappa_A T_1 + \kappa_A T_2 + \dots + \kappa_A T_{u-2} + \kappa_{ac} T_{u-1} &< 1 & i &= (u-1)^* \end{aligned} \quad (12)$$

Equalities (11) demonstrate that critical damage leading to initiation of crack will occur in the most vulnerable cross-sections of the stud  $i=1^*$  and  $i=u^*$ , respectively. In contrary to the previous problem, inequalities (12) show that the remaining cross-sections  $i$  ( $1^* < i < u^*$ ) are below the critical damage value equal to 1. It can also be observed that the above cross-sections of the stud are unloaded by shifting the nut before cracking.

The value of the equivalent number of loading cycles is obtained by solving equations (11). The solution in terms of critical cycling numbers gives the expression:

$$T_{eq} = \frac{N_{0C}(N_{0A} - N_{0C})}{d_h N_{0A} + (u-2)N_{0C}} \quad (13)$$

while the total number of loading cycles is:

$$T_{sum} = N_{0C} + (u-1)T_{eq} \quad (14)$$

**Model III.** The problem is formulated by assuming the equivalence of all the loading periods  $j=1, 2, \dots, u$ . Each of them is characterised by a constant number of loading cycles, i.e.  $T_j = T_{eq} = const$ . It is easy to demonstrate that the solution may be obtained from the last equation (11) and is expressed as follows:

$$T_{eq} = \frac{N_{0A}N_{0C}}{d_h N_{0A} + (u-1)N_{0C}} \quad (15)$$

This solution transforms the remaining



equations into strong inequalities. As a result, the crack is initiated only in the single section of the stud  $u^*$ , while the entire stud remains within the safety limits.

Thus, the fatigue life limit is defined by the total number of loading cycles:

$$T_{sum} = uT_{eqt} \quad (16)$$

A comprehensive analysis of the above cases and discussion will be given in the following sections.

### 3. Crack initiation indexes

Examination of fatigue damage accumulation has highlighted that two critical parameters  $N_{0C}$  and  $N_{0A}$  play a decisive role in the prediction and prolongation of the fatigue life of the threaded joint. Evaluation of the above two parameters should be carried out in the preliminary investigation stage by analysis of the routine cyclic loading of the threaded joint.

The crack initiation indexes in the stud  $N_{0C}$ ,  $N_{0A}$  and thus the rate  $N_{0A}/N_{0C}$  can be determined by analysis of the routine cyclic loading of the threaded joint when the periodical varying of the relative position of stud and nut is not applied.

The thread loads and local stresses in stud roots have to be calculated primarily for these purposes. Consequently, the characteristic sections  $C$  and  $A$  are examined in detail.

It is known that the local stresses at an arbitrary cross-section of the stud are caused by both the distributed turn load  $q(z)$  and internal axial force  $Q(z_C)$  ( $Q(z) = \int_0^z q(z)dz$ )

which acts in the core of the stud. Here  $q(z)$  is defined as load per unit length added along height  $H$  of the joint.

The stud turns located in the cavity of the bush-washer, i.e. in the cross sections  $A$  of the threaded joint, are unengaged. Therefore, the local stresses in roots of these turns are caused exclusively by the axial internal force  $Q(z_A)$  which acts in the core of the stud and is equal to the external load  $F$  acting on the threaded joint.

We assume again that the highest local stresses occur in the vulnerable section of the stud. This section indicates the root of the stud turn engaged with the dangerous turn of the nut in section  $C$  of the joint. Thus, the stresses at cross-section  $z_C$  arise due to the maximum turn load  $q(z_C)$  and the load  $Q(z_C)$  which acts in the core of the stud. The values of the loads  $q(z_C)$  and  $Q(z_C)$ , where  $Q(z_C) = \int_0^{z_C} q(z)dz$ , have been obtained from the calculation of the load distribution along the thread of the joint.

In order to illustrate the performance and application of our development, an evaluation of the critical parameters below was carried out through the analytical method given in [20, 30]. The threaded joint M20×2.5 having a diameter  $d=20$  mm, height of the nut  $H=0.8d=16$  mm and thread pitch  $P=2.5$  mm is used as an example in the following consideration.

The chemical composition of the joints M20×2.5 material i.e. of the stud and nut steel is (wt. %): 0.36 C, 0.22 Si, 0.39 Mn, 1.45 Cr, 3.30 Ni, 0.10 Cu, 0.41 Mo, 0.14 V, 0.009 S, 0.015 P. The average indices of the mechanical properties of the joint steel (after normalization) are the following: proof

strength  $R_{p0.2}=900$  MPa, tensile strength  $R_m=1020$  MPa, percentage area of reduction  $Z=58.5$  % and module of elasticity  $E=210$  GPa

Two loading levels of the joint M20×2.5 with external maximum cyclic loads responding to relative nominal stress of the stud  $\sigma_{n,max}/R_{p0.2}=0.59$  and  $\sigma_{n,max}/R_{p0.2}=0.85$  are considered respectively. The nominal stress is  $\sigma_n=F/A_s$ , where  $A_s$  denotes the cross-sectional area of the stud core. Variations of the loads along the joint height  $H$ , where  $0 \leq z \leq H$ , are presented in Fig. 2.

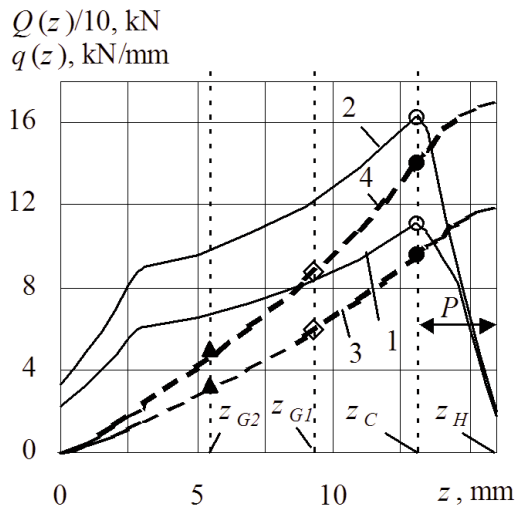


Fig. 2. Variation of thread loads  $q(z)$  and  $Q(z)$  along the joint threads for various relative nominal stress  $\sigma_{n,max}/R_{p0.2}$ : 1 –  $q_1(z)$  for  $\sigma_{n,max}/R_{p0.2}=0.59$ ; 2 –  $q_2(z)$  for  $\sigma_{n,max}/R_{p0.2}=0.85$ ; 3 –  $Q_1(z)$  for  $\sigma_{n,max}/R_{p0.2}=0.59$ ; 4 –  $Q_2(z)$  for  $\sigma_{n,max}/R_{p0.2}=0.85$ ; o –  $q(z_C)$ ; • –  $Q(z_C)$ ; ◊ –  $Q(z_{G1})$ ; ▲ –  $Q(z_{G2})$

In order to estimate a fatigue life until the crack initiation (critical number of loading cycles  $N_0(z)$ ) in the stud roots, the modified standard method [24] based on Coffin-Manson-Langer type formula was applied. A

modification elaborated in [20] was performed for a more accurate calculation of the local stresses in the roots of the stud by estimation of the influence of the load distribution along the joint thread.

The validation of the modified method [20] was confirmed through the comparison of the calculation data with the results of the experiments carried out. The data of 294 low fatigue tests of the threaded M16, M20 and M42 joints presented in [20] are applied for these purposes. A magnetic luminescent powder method was used during the experiments to detect the crack initiation in the tested studs. The critical number of cycles indicating the crack initiation is fixed when the length of the macrocrack around the periphery reaches (3÷6) mm.

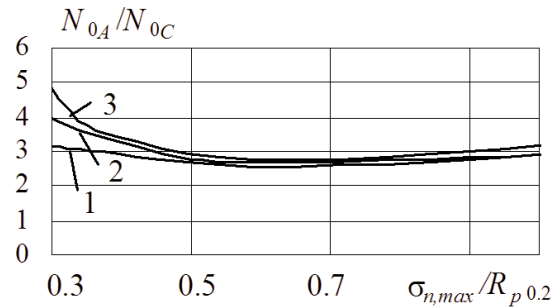


Fig. 3. Variation of index  $N_{0A}/N_{0C}$  for stud M20×2.5 against relative stress  $\sigma_{n,max}/R_{p0.2}$  for the various values of the loading asymmetry factor  $r$ : 1 –  $r=0$ ; 2 –  $r=0.3$ ; 3 –  $r=0.6$

It is easy to confirm that the critical values  $N_{0A}$  and  $N_{0C}$  as well as the index  $N_{0A}/N_{0C}$  depend on the material properties and symmetry of the loading cycle.

The nature of these relationships is illustrated in Fig. 3. Here, the variation of the index  $N_{0A}/N_{0C}$  against the relative stud nominal maximum stress of the stresses

cycle  $\sigma_{n,max}/R_{p0.2}$  for the specified values of the asymmetry factor  $r=\sigma_{n,min}/\sigma_{n,max}$  of the external cyclic loading is shown. It is obvious from the graph in Fig. 3 that theoretically the cyclic lifetime of the joints M20×2.5 can be prolonged by more than two times.

The above results illustrate the theoretical limits which could be applied for the preliminary evaluation of the cyclic strength of the threaded joint. A detailed analysis basing on explication of positioning and loading cycles is required; however, to predict the real possibilities to prolong the cyclic lifetime of the joint.

#### 4. Increasing the threaded joint lifetime

Increasing the lifetime of the threaded joint M20×2.5 is considered by applying three positioning models described in Section 2. The cyclic lifetimes are calculated by using methodology [20]. The joint material is insensitive to non-stationary loading, therefore factor  $d_h=1$ .

Selected results showing the fatigue life prolongation possibilities for the bolted joint M20×2.5 are presented in Figs. 4 and 5. The graphs in Fig. 4 present variations of the relative loading cycles  $T_{sum}/N_{0C}$  against an increased number of positioning periods  $u$ . Here, curves 1 respond to the results of *model I* obtained by expressions (9), curves 2 respond to the results of *model II* obtained by expressions (14) and curves 3 respond to the results of *model III* obtained by expressions (16). Each of the above families of the curves contain results obtained for two relative maximum nominal stresses,  $\sigma_{n,max}/R_{p0.2}=0.85$  drawn by solid lines and

$\sigma_{n,max}/R_{p0.2}=0.59$  drawn by dot lines, respectively. Presentation of the results is limited by considering the asymmetric cyclic loading with  $r=0.6$ , which is similar to the characteristic loads of the threaded joints.

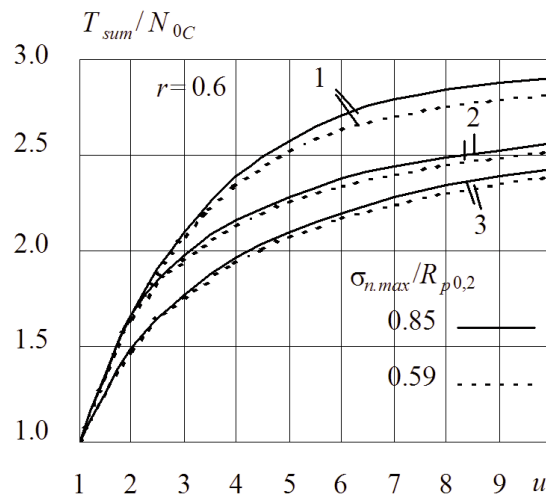


Fig. 4. Influence of the initial conditions to prolong of the lifetime of threaded joint: 1 – model I; 2 – model II; 3 – model III

The results confirm that the restriction-free *model I* yields the optimal solution defined by the highest values of the total numbers of the loading cycles. Almost three time prolongation could be expected after ten periods,  $u=10$ . The restrictions requiring an equality of all the positioning periods  $T_j=T_{eq}=const$  in *model II*, when  $j > 2$  and different critical loading during the first period  $T_1=N_{0C}$  reduces efficiency of the positioning which drops until 2.5 times. An additional requirement on equality of all the loading periods in *model III* insignificantly reduces efficiency.

A detailed cycle-by-cycle analysis

obtained by expressions (8), (13) and (15) is illustrated in Fig. 5 by column diagram for the case of four loading periods ( $u=4$ ). Here, the relative durations of the cyclic loading periods are shown. Thereby, each column contains three sub-columns reflecting the results obtained by all three positioning models.

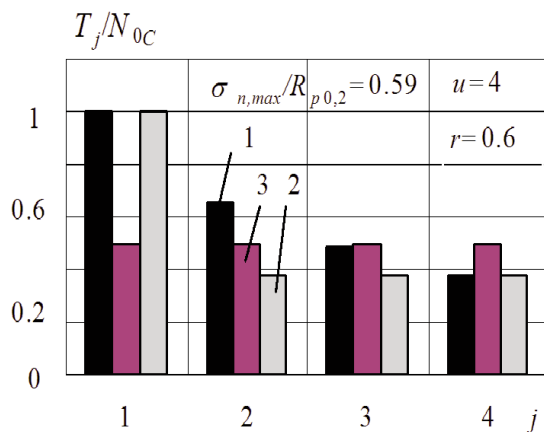


Fig. 5. Relative duration of the cyclic loading periods: 1 – model I; 2 – model II; 3 – model III

Fig. 5 clearly illustrates the influence of restrictions to relative duration of every loading period  $T_j/N_{0C}$  imposed by model II ( $T_1=N_{0C}$  and  $T_2=T_3=T_4=T_{eq}$ ) and model III ( $T_1=T_2=T_3=T_4=T_{eq}$ ) upon comparing these two models with the restriction-free model I.

The analysis presented above demonstrates the real possibility to prolong the overall cyclic lifetime of the threaded joint up 2.5 times

Thereby, the stud cross-sections with cracks after its shifting in depth of the nut still should be sufficiently secure. An analysis of this problem and subsequent discussion are in the following sections.

### 5. Prediction of the stud’s crack growth in depth of the nut

As shown in Section 2, the stud cross-section with a crack, formed in the position  $C$  of the threaded joint, is shifted in depth of the nut if the considered method for increasing cyclic strength of the threaded joint is used. At first in the joint’s section  $G_1$  and later in the sections  $G_2, G_3, \dots$  where considerably lower axial force  $Q(z) < Q(z_C)$  acts on the stud core with crack (Fig. 2). Consequently, according to the concept of unloading the cracked stud cross-section, this crack in depth of the nut can be almost frozen i.e. the growth rate of this crack becomes considerably lower in comparison to its growth rate which would be in the risky section  $C$ . It is obvious that the efficiency of this procedure depends on the crack shifting distance  $\Delta H$ .

The purpose of this Section is to verify the efficiency of unloading the stud cracked cross-sections from a fracture mechanics viewpoint.

The loading conditions of the stud crack with it being in the nut depth can be quantitatively characterized by the ratio  $N_{st}(z)/N_{st}(z_C)$ . This ratio makes it possible to compare the eventual cyclic duration  $N_{st}(z)$  of the crack stable growth in any stud cross-section  $z$ , located in depth of the nut, with the eventual cyclic duration  $N_{st}(z_C)$ , of the crack stable growth in the stud cross-section which is located in the risky section  $C$  of the nut. Since resistance of the cracked stud to cyclic loading is mostly predefined by contribution of the stable crack growth, contribution of initial and unstable cyclic cracking stages has been neglected in the below comparison.

Prediction of the stud crack growth with it being in the depth of nut for the considered threaded joints M20×2.5 was performed by applying the same principles which were used to describe its fatigue fracture experienced during the conventional low fatigue tests of 31 specimens [20, 31]. The results of the quantitative prediction of the ratio  $N_{st}(z)/N_{st}(z_C)$  are presented in this Section after clarification of calculation methodology.

The eventual cyclic durations  $N_{st}(z)$  and  $N_{st}(z_C)$  were calculated through the integration of the well known Paris equation, which relates the stable crack propagation rate  $dh/dN$  with the range of the stresses intensity factor  $\Delta K_1 = K_{1,max} - K_{1,min}$ , where  $K_{1,max}$  and  $K_{1,min}$  are the maximum and minimum values of the stress intensity factors of the loading cycle. The Paris equation constants were obtained from the experimental data of 31 conventional fatigue tests of joints M20×2.5, presented in [31], with attention being given to the macrocrack growth stage in the cross-section  $z_C$  of the stud.

In order to calculate the stress intensity factor  $K_1(z)$  of the stud stable crack the formula derived by S. Jarema for the cylindrical rod with crack [32] was used. Having applied this formula the stresses around the crack tip are only determined by the axial force  $Q(z)$  which acts in the stud core. The appropriate turn load  $q(z)$  effects only the shallow (initial) crack and does not influence the stable crack which is deeper.

In the calculations of the eventual cyclic duration  $N_{st}(z)$  the stable crack limit depth  $h_{cr}(z)$  for any stud's cross-section have been defined by using conditions of the validity of

the linear fracture mechanics [33]. It was assumed that unstable cyclic cracking occurs when crack depth overrun limit depth  $h_{cr}(z)$ .

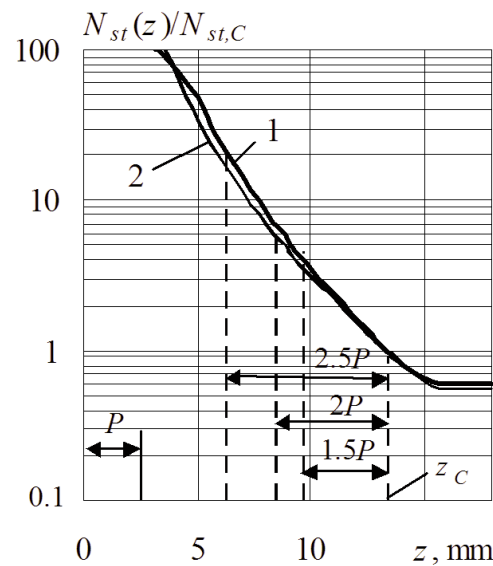


Fig. 6. Relative duration of the stable growth of stud crack in depth of the nut: 1 –  $\sigma_{n,max}/R_{p0.2}=0.59$  and  $r=0, 0.3, 0.6$ ; 2 –  $\sigma_{n,max}/R_{p0.2}=0.85$  and  $r=0, 0.3, 0.6$

The calculation results for the prediction of the ratio  $N_{st}(z)/N_{st}(z_C)$ , which reflects the efficiency of the stud crack growth, with it being in the nut depth, are presented in Fig. 6.

Fig. 6 shows that the eventual cyclic durations of the stud (M20×2.5) crack growth  $N_{st}(z)$  are 4.5, 6 and 18 times greater than  $N_{st}(z_C)$ , if this crack grows in the stud cross-sections which are in depth of the nut and remote from the section C by distances 1.5P, 2P and 2.5P respectively. Every section of the nut mentioned above can be considered as position  $G_1$  (Fig. 1b) where the stud crack can be put after the first nut shifting.

It is therefore obvious that the stud crack growth can not be completely frozen in the nut zone  $P < z < z_C$  but can be considerably prolonged.

### 6. Relative safety factors for the unloaded stud cracks

According to the procedure intended by the cracks unloading method, the particular stud cross-sections with recently formed cracks before loading periods  $T_2, T_3, \dots$  are shifted in the secure place i.e. in depth of the nut. In this Section, the safety of these stud cross-sections after its shifting are defined from the view point of the cyclic strength of the whole stud.

During any loading period  $T_j$ , the most dangerous stud cross-section is the one located in the risky section  $C$  of the joint. Thereby, it is possible to presume that the cyclic lifetime resource of the cracked stud cross-section located in depth of the nut in this time is far greater than that of the dangerous stud cross-section. Thus, the safety of any cracked and unloaded stud cross-section is defined by a relative safety factor expressed in the following form:

$$k_{j,Gi} = \frac{N_{st}^*(z_{Gi})}{T_j + N_{st}(z_C)} \quad (17)$$

where  $N_{st}^*(z_{Gi})$  is the remaining cyclic duration of the crack stable growth in the stud cross-section  $z_{Gi}$  where the crack occurs at the beginning of the loading period  $j \geq 2$  ( $T_j + N_{st}(z_C)$ ) is the remaining cyclic lifetime of the stud cross section  $z_C$

at the beginning of the same loading period  $j$ ,  $z_{Gi}$  is the length coordinate of the considered stud cross-sections with crack (i. e.  $z_{G1}, z_{G2}, \dots$ ).

The lowest value from  $k_{2,G1}, k_{3,G1}$  and  $k_{3,G2}$  shows which crack is the most dangerous. If the lowest value of the relative safety factor is unaccepted, the nut moving distance  $\Delta H$  must be increased.

It has been defined by calculations that the lowest value of the relative safety factor for the considered threaded joints M20×2.5 is  $k_{2,G1}$ . This value reflects the relative safety of the first stud crack at the second loading period  $T_2$ .

The dependence of the relative safety factor  $k_{2,G1}$  on the crack shifting distance in depth of the nut for the optimal case (*model I*) is shown in Fig 7. If the crack formed in the stud cross-section  $z_C$  is shifted in depth of the nut by distances  $\Delta H=1.5P, \Delta H=2P$  or  $\Delta H=2.5P$ , then the relative crack safety factor takes values in the following ranges  $k_{2,G1}=(2.4-3.2), k_{2,G1}=(4-5.5)$  or  $k_{2,G1}=(7-10)$  respectively. Fig. 7 shows that in the ranges of the example, the lowest values this factor have at the loading level  $\sigma_{n,max}/R_{p0.2}=0.85$  and loading asymmetry  $r=0.6$ .

In calculation Standards [24] the required safety factor for the conventional threaded joints with regard to low cycle lifetime is  $n_N=5$ . The same value can be accepted for the first consideration in a viewpoint to the relative safety factor  $k_{2,G1}$ . Fig. 7 shows that in the case when  $k_{2,G1}=5$  is required, the distance of crack shifting in the nut depth would be

$\Delta H \geq 2.2P$ .

It is obvious that the conventional safety factor must be used also when the crack unloading method is applied. This reduces calculated values of the loading periods to  $n_N$  times i.e. its real durations are  $T_1/n_N, T_2/n_N, T_3/n_N, \dots$

Thus, the safety of the stud cross-sections which periodically comes in to position C from the cavity of the bush-washer is regulated by the safety factor  $n_N$  as in the case of the conventional operation of the threaded joint. The safety of the cracked stud cross-sections which periodically occur in depth of the nut are regulated by both the conventional safety

factor  $n_N$  as well as the related safety factor  $k_{j,Gi}$ .

Thus, the quantitative analysis presented in this Section demonstrates that cracked stud cross-sections can be sufficiently secured by regulation of the distance  $\Delta H$  of the crack shifting in depth of the nut.

### 7. Conclusions

Investigation of the cyclic strength of the axially loaded threaded joints behaviour demonstrates possibility to prolong their fatigue life. In summary of the obtained results, the following conclusions can be drawn:

- Mathematical model describing accumulation of the fatigue damage as well as the crack growth in the roots of the stud thread is suggested. Applications of the model demonstrates that the model allows control safety of the threaded joint through the unloading of cracked sections and how to exploit resources of the threaded joint after opening of the crack without reduction of the safety

- On the basis of the above model the procedural method to increase the lifetime of the threaded joint is elaborated. The method operates by varying the mutual positions of the stud and the nut. It was found that the stud crack growth rate can be noticeably retarded due to its unloading by moving the nut.

- Prolongation of the lifetime of the threaded joint can be theoretically evaluated by the non-dimensional prolongation factor defined as a ratio of

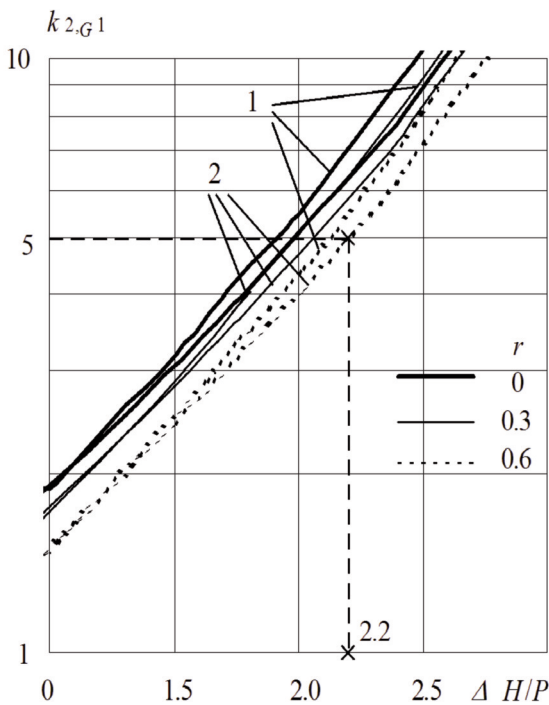


Fig. 7. Variation of the crack unloading factor against the crack shifting distance in depth of the nut: 1 –  $\sigma_{n,max}/R_{p0.2}=0.59$ ; 2 –  $\sigma_{n,max}/R_{p0.2}=0.85$

the numbers of loading cycles required to initiate cracks in the roots of unengaged and most dangerous engaged turns of the stud.

- The characterizing of the stud crack growth in the depth of the nut can be done by applying the crack growth indexes experimentally obtained during conventional cyclic loading of the threaded joints.

- Comparison of the presented developments with standard safety requirements shows that the restriction on the growth of the studs crack recently formed in the risky position is completely fulfilled. It should be noted, however, that the multiple crack initiation in the stud thread is possible. Multiple cracks occur after each of the loading periods and are located in different places of the stud thread.

- Formally, the growth of the crack in the safety depth of the nut is not prevented, therefore, additional control through applying the relative safety factors is obligatory.

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