VILNIUS GEDIMINAS TECHNICAL UNIVERSITY

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DEFORMATION AND STRENGTH OF A CYCLICALLY BENT THREADED CONNECTION

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Introduction

Formulation of the problem and topicality of the thesis. Industry equipment such as pressure vessels, mining equipment, heat exchangers, steam generators and other structures are provided with bolted closures for the purpose of in-service inspection and maintenance of internal components. Threaded connections often experience variable cyclic loads due to temperature, inner pressure and variation in the deformation of connection fittings. Often, studs and screws are not only affected by an axial load, but also by bending moments.

More sophisticated high-cycle and low-cycle durability calculation methodologies have been already developed for threaded connections experiencing cyclic axial loads, and in these methodologies the distribution of axial load among turns is assessed quantitatively. The quantitative data of load distribution in the thread enables a more accurate assessment of the influence of the constructional design particularities (connection length, material, nut and turn's form) and the deformation stages of the connection element.

These durability calculation methodologies are not applied for threaded connections that are cyclically bent, as the analytical models that are suitable for practical application in the load distribution of the turns have not been created for bent threaded connections. In this field, no models have been created to be calculated by the BE method.

As the threaded connection is a complex node consisting of deformed elements, the load distribution among turns is influenced by the compatibility of the deformations and displacements of the connection elements. While mathematically describing the deformed state of the connection, theoretical and experimental data is needed to reflect the specific features of the deformation of the connection elements that occurs during the bending operation.

This dissertation thesis aims to create a calculation methodology for the load distribution in the thread, intended for threaded connections cyclically bent, and to apply this methodology for the calculation of cyclic strength.

Object of the Research. Cyclically bent threaded connection.

Aim and Tasks of the Work. The aim of the present work is to create a models of load distribution in the turns of a cyclically bent threaded connection and apply its for the normative cyclic durability calculation. There are few tasks under consideration:

1. Experimentally determine the pliability indices of thread turns, unloaded and repeatedly loaded.

2. Create a scheme of the elastic deformation of the elements of bent threaded connections and the differential compatibility equations of their displacements: a) when the thread turns are engaged over the full profile, b) when the thread turns are partly engaged. Determine the approximate analytical solutions for differential equations describing the bending load distribution in turns, and verify them by numerical methods.

3. By applying solutions of differential equations create a model of three segments for a case when the connection is eccentrically tensioned, and a multi-segmental model for a case when the threaded connection is bent after tightening.

4. Apply a models of load distribution in the turns for a normative calculation of the cyclic durability of bent threaded connections and verify the calculation results on the basis of experimental data.

5. Suggest ways to increase the durability of the threaded connection, and to decrease the local stresses in the danger zone of the threaded connection. Create their mathematical models.

Methodology of Research. The research has been performed on the basis of analytical, numerical and experimental methods.

Scientific Novelty

1. An original scheme of the deformation of bent threaded connection is proposed and the differential compatibility equations of displacements relating the deflections of the turns with the angular displacements of the stud's and nut's cross-sections are created.

2. Two models of bending load distribution in the threaded connection have been created: a) a three-segmental model of a threaded connection eccentrically tensioned, b) a multi-segmental model of a bent threaded connection after tightening.

3. The pliability indices of single turn pairs of the thread repeatedly loaded have been experimentally determined.

4. A cyclic durability improvement method has been created, which has been implemented with periodical changes in the connection's position with respect to the bending plane. A pre-overloading method has been created to reduce the local stresses in the thread of the stud. Mathematical models have been created for both methods.

Practical Value. The work results allow a more accurate assessment of the impact of bending load and the influence of structural factors on the load distribution in the turns of the thread, plus a more accurate prediction of the cyclic durability of the bent threaded connections. The periodic change method of positions between the connection and the bending plane allows for increasing the durability of the threaded connection being cyclically bent.

Defended Propositions

1. A significant pliability change in a pair of turns of the thread occurs after the first loading while unloading and repeatedly reloading.
2. Created three-segmental and multi-segmental models of the bent threaded connection assess the irregularity of turns engagement and loading order of the turns – loading or unloading – in cases of the eccentric tension and bend after tightening of the threaded connections. The application of models adjusts the durability calculation of the threaded connections being cyclically bent.
3. Periodic changes in the position of the connection with respect to the bending plane increases the durability of the threaded connection being cyclically bent. Pre-overloading of the connection reduces the local stresses of the thread of the stud in the risky areas of the connection.

Approval of the Work. Nine presentations on the topic of the dissertation thesis were delivered at scientific conferences and seminars in Lithuania and abroad, and nine articles were published.

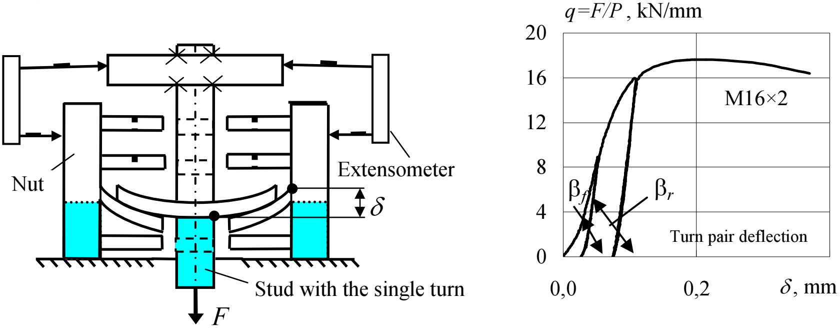
The Scope of the Scientific Work. The dissertation consists of an introduction, 5 chapters, general conclusions, list of references, and a list of the author's publications. The dissertation comprises 122 pages, including 64 illustrations.

1. Cyclic Strength and Deformation of the Threaded Connections

Due to temperature, inner pressure and variation in the deformations of the connection fittings, the threaded connections of industrial equipment not only often experience axial, but also cyclic bending loads. The serious stress concentrations existing at the thread roots often cause the danger of low cycle fatigue failure of the connectors. The load distribution along the threads has a direct influence on the stress at the thread roots. Up to now, high and low cycle fatigue calculating methods have not directly used the data of the bending load distribution in the thread. Instead of it, the influence of some structural features on the cyclic durability at a given point have only been approximately evaluated by constant factors. That is insufficient, because many of the structural parameters of the threaded connections which influence the load distribution have been designed in a wide range of dimensions. The distribution of the bending loads in a thread depends on its deformation, which has not been estimated in existing models. A more trustworthy way for a more exact calculation of the stresses and fatigue of threaded connections is the direct use of load distribution data. Analysis of these field investigations has shown that there is lack of scientific research.

2. Experimental Investigation of the Turn Pair Deformation Properties

In order perform a more accurate research of the fatigue phenomena of threaded connections and calculation of cyclic strength, data is necessary on the deformation properties of turn pairs, when turn pairs experience the first and then their recurrent reloading – unloading. Their pliability indices were determined while performing the tension tests of single turn pair, M16 and M20 (Fig. 1 a).



a b

Fig. 1. A single turn pair tension test (a), an experimental turn pair tension curve (b)

The experimental turn pair tension curve (Fig. 1 b) shows that turn deformation is apparently not a reversible process. It has been determined that the turn pair pliability value γ_f ($\gamma_f = \cot\beta_f$) of loading for the first time in the initial linear stage is 2–2.4 times greater than the pliability γ_r ($\gamma_r = \cot\beta_r$), which the turn pair possesses while unloading for the first time and repeatedly reloading and unloading.

3. Elastic Models for the Bent Threaded Connections

This chapter presents elastic models of load distribution in the turns and calculation results for a case of eccentrically tensioned thread connection and for a case when after tightening, the connection only suffers bending.

The model of a bent threaded connection in three segments. The research object of this sub-chapter is a threaded connection: a stud with a compressed nut, which after the assembly of the fitting elements is tightened, and during operation it suffers from repeated eccentric tension. The threaded connection is subjected to an axial force F_t, and an external bending moment M_f (Fig. 2).

The distributed longitudinal turns load $q_t(z)$, occurring due to the action of the axial force F_t, was calculated by applying the earlier created model (Selivonec, Krenevičius 2004).

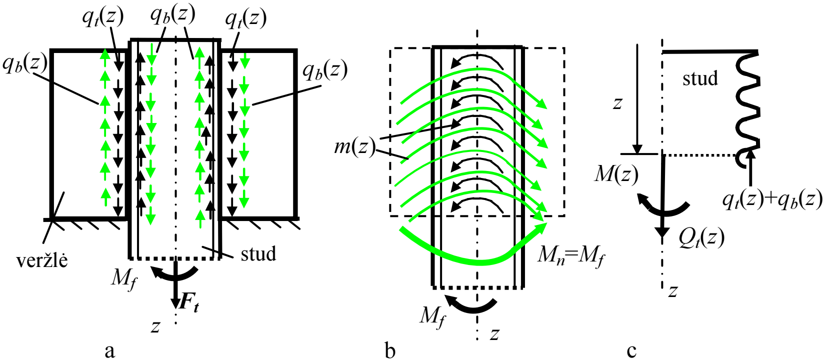


Fig. 2. Intensities of thread loads (a), bending moments (b), turn loads and internal forces caused by local stresses in the stud thread

The model created in this dissertation thesis is based on calculation of the distributed longitudinal turns load $q_b(z)$, which occurs due to the impact of the bending moment M_f (Fig. 2). The loads of turns are distributed on the turns' helix, corresponding to the middle thread diameter of $2R$.

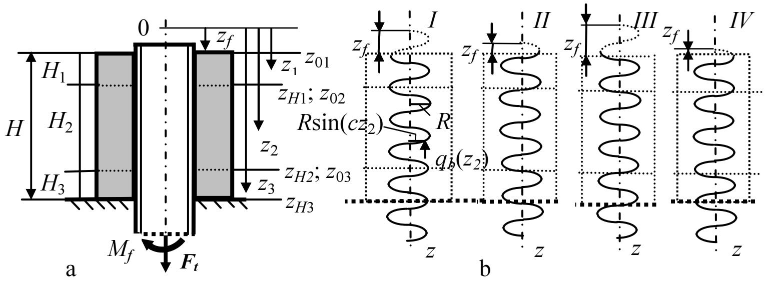


Fig. 3. Segments of a threaded connection (a), four particular helix positions, with respect to the bending plane in the bent threaded connection (b)

The distributed load of turns $q_b(z)$, which has the arm $R\sin(cz)$, with respect to the neutral line NL (suppose that moment M_f acts alone), causes the distributed bending moment $m(z)$ and the respective inner bending moment $M(z)$, which acts in the stud's core and the nut's wall (Fig. 2):

$$m(z) = q_b(z)R\sin(cz)\,, \qquad\qquad M(z) = \int_0^z m(z)dz \tag{1}$$

The position of the helix with respect to the bending plane, i.e. position of the sinusoid $R\sin(cz)$, is regulated using the sinusoid's initial phase length z_f, which determines the beginning of the reference of coordinate z_i of the connection cross-sections (Fig. 3). In the middle segment of the discrete model of the threaded connection H_2, the turns are engaged over the full profile, and their pliability is constant through the entire length $\gamma(z_2) = \gamma_f = const$. The runouts are schematized by marginal model segments, whose length is equal to a thread pitch, $H_1 = P$ and $H_3 = P$. Due to the variable depth of the turns contact, the pliability of the turn pairs fluctuates in the runouts, and in the model it is described by a following equation (where $i = 1; 3$ and V_i, and u_i are constant coefficients.)

$$\gamma(z_i) = V_i e^{u_i z_i} \tag{2}$$

In Fig. 4, it is possible to observe that the stud's and the nut's cross-sections in the bent threaded connection deflect in the opposite directions.

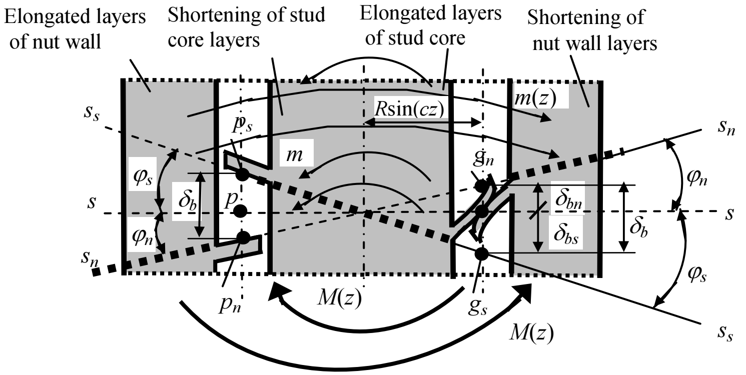


Fig. 4. Displacements of the stud and nut cross-sections and the deflections of the turns

The angular displacement of the stud's and nut's cross-sections φ_s and φ_n are compensated by the stud's and nut's turn deflections, δ_{bs} and δ_{bn}. Their sum makes the deflection of the turn pair $\delta_b = \delta_{bs}+\delta_{bn}$. Thus, the turn pair deflection, acquired on one side from the neutral line (*NL*) due to the action of the turns loads increases, and on the other side – decreases. The relation between the turn deflections and turn loads, and the angular displacements of the cross-sections and turn deflections can be expressed by the following equations.

$$\delta_b(z) = \gamma(z) q_b(z) \tag{3}$$

$$\varphi_s(z) \approx \tan\varphi_s(z) = \frac{\delta_{bs}(z)}{R\sin(cz)}, \qquad \varphi_n(z) \approx \tan\varphi_n(z) = \frac{\delta_{bn}(z)}{R\sin(cz)} \tag{4}$$

Differences in the angular displacements of the stud's and nut's cross-sections in any part of a connection segment $\varDelta z = z\text{-}z_0$ are equal to $\varDelta\varphi_s(z) = \varphi_s(z) - \varphi_s(z_0)$ and $\varDelta\varphi_n(z) = \varphi_n(z) - \varphi_n(z_0)$. Their relation with the respective deflections of the turn pairs is as follows:

$$\varDelta\varphi_s(z) + \varDelta\varphi_n(z) = \frac{\delta_b(z)}{R\sin(cz)} - \frac{\delta_b(z_0)}{R\sin(cz_0)} \tag{5}$$

Applying the relation between angular displacements and inner bending moments, which is given by a differential equation concerning straight bar deflections and using formula (5), the following integral compatibility equation of the deflections of threaded connection elements was obtained:

$$\lambda \int_{z_0}^{z} M(z_0)dz + R\lambda \int_{z_0}^{z}\int_{z_0}^{z} \frac{\delta_b(z)}{\gamma(z)} \sin(cz) d(z) = \frac{\delta_b(z)}{R\sin(cz)} - \frac{\delta_b(z_0)}{R\sin(cz_0)} \tag{6}$$

where E_s, E_n and I_s, I_n are the elasticity modulus of the stud's and nut's cross-sections and the axial moments of inertia, which result in the expression $\lambda = 1/(E_s I_s) + 1/(E_n I_n)$.

Entering the turn deflection amplitude function $y(z) = \delta_b(z)/\sin(cz)$ to the equation (6), and after differentiation of the equation (6), the differential equation relevant to segment H_2 was obtained, and the differential equations for the segments H_1 and H_3:

$$y''(z) - R^2\lambda[y(z)/\gamma_f]\sin^2(cz) = 0 \tag{7}$$

$$y''(z) - R^2\lambda[y(z)/\gamma(z)]\sin^2(cz) = 0 \tag{8}$$

The approximate solutions determined for equation (7) for the segment H_2, where $z = z_2$, $b = R\lambda/\gamma_f$ and $K_f = R/[\gamma_f(n^2+4c^2)]$, yield these equalities:

$$y(z) = A\sinh(nz) + B\cosh(nz), \qquad n = \sqrt{-2c^2 + c\sqrt{4c^2 + 2b}} \tag{9}$$

$$M(z) = AF_{fA}(z) + BF_{fB}(z) \tag{10}$$

$$F_{fA}(z) = K_f\left[n\cdot\cosh(nz)\sin^2(cz) - c\cdot\sinh(nz)\sin(2cz) + \frac{2c^2}{n}\cosh(nz)\right] \quad (11)$$

$$F_{fB}(z) = K_f\left[n\cdot\sinh(nz)\sin^2(cz) - c\cdot\cosh(nz)\sin(2cz) + \frac{2c^2}{n}\sinh(nz)\right] \quad (12)$$

The approximate solutions of equation (8) for the runouts, where $z = z_1$ or $z = z_3$, have been obtained in the following form

$$y(z) = Ae^{n_A z}(n_A z + W_A) + Be^{n_B z}(-n_B z + W_B) \quad (13)$$

$$M(z) = AF_{pA}(z) + BF_{pB}(z) \quad (14)$$

$$F_{pJ}(z) = \frac{R\cdot e^{t_J z}}{2V_i}\left[\pm\frac{n_J(t_J z - 1)}{t_J^2} \mp n_J\left(\left(t_J z - \frac{t_J^2 - 4c^2}{p_J}\right)\frac{\cos(2cz)}{p_J} - \left(\frac{4ct_J}{p_J} - 2cz\right)\frac{\sin(2cz)}{p_J}\right) - \frac{W_J}{p_J}\left(t_J\cos(2cz) + 2c\sin(2cz)\right) + \frac{W_J}{t_J}\right] \quad (15)$$

where $J = A$ or $J = B$, $t_J = n_J - u_i$ and $p_J = t_J^2 + 4c^2$, and the power exponents n_A, n_B and coefficients W_A ,W_B are determined after solving the two additional special systems of the equations.

In order to determine the constant factors A_i and B_i, present in the equations (9, 10, 13, 14) of the solutions for the three-segmental bent connection, the equations system was used for expressing the known boundary conditions made in the junction of the connection segments: $M(z_{01}) = 0$, $M(z_{H1}) = M(z_{02})$, $M(z_{H2}) = M(z_{03})$, $M(z_{H3}) = M_f$, $\delta_b(z_{H1}) = \delta_b(z_{02})$, $\delta_b(z_{H2}) = \delta_b(z_{03})$.

According to the model created, calculations were performed for the connections M16×1, M16×1,5, M16×2, M52×4 and M110×6. Calculations for the M16×2 connection were carried out utilizing the four different helix positions of I, II, III and IV, as indicated in Fig. 3. The control of the accuracy of the approximate analytical solutions was accomplished by using the comparison of the calculation results obtained by the analytical and numerical Runge-Kutta method. The numerical values of the functions $y(z_i)$ and $M(z_i)$, determined by the analytical and Runge-Kutta methods only slightly differ; no more than by 1%.

The three-segmental bent threaded connection model is suitable for eccentric loading cases, when $q_t(z)$-$q_b(z) \geq 0$. Only in this case, the turns in both sides of the connection from the *NL* have equal pliability values.

Local alternating elastic stresses in the stud's thread. Calculation examples of local stresses $\sigma*(z)$ of stud's thread M16×2 are presented in Fig. 5.

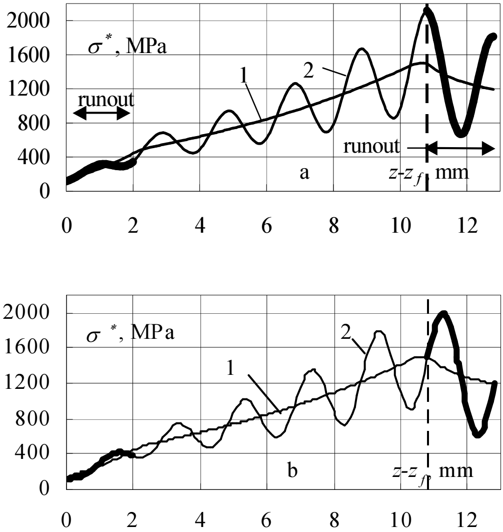


Fig. 5. Local alternating stresses in stud threads M16×2: helix position *I* (a), helix position *III* (b): *1* – stresses due to tension, *2* – stresses due tension and bending

The maximum local alternating elastic stresses in a stud's thread $\sigma^*(z)$ (used to check the cyclic strength), which appear in the cross-section z, depend on the values of $Q_t(z)$, $M(z)$, $q_t(z)$ and $q_b(z)$ (Fig. 1). These stresses have been calculated according to Machutov's formula (1987), which in this thesis, was also applied for cases when the effects of bending exist. The calculation formula obtained for the local stresses expresses this sum as follows:

$$\sigma^*(z) = \sigma_t^* + \sigma_b^* = K_{t,m}\frac{q_t P}{f} + K_{t,0}\frac{Q_t}{A_s} + K_{b,m}\frac{q_b P}{f} + K_{b,0}\frac{M}{I_s}R_v\sin(cz) \quad (16)$$

where σ_t^*, σ_b^* – local thread's stresses in stud's cross-section z, caused by connection tension and bending; $K_{t,m}$, $K_{b,m}$ – stresses concentration coefficients, which assess the impact of turn loads; $K_{t,0}$, $K_{b,0}$ – stresses concentration coefficients, which assess the impact of inner force of stud's core and inner bending moment; f – projection of turn contact surface to plane perpendicular to stud's axis; A_s – cross-sectional area of stud's core.

Nut's length of considered connection is $H = 0.8d = 12.8$ mm. Connection is made from steel 25X1MΦ (21CrMoV5-7 according EN 10083-3). Nominal tension and bending stresses in the stud's core are respectively $\sigma_{t,nom}/R_{p0.02} = 0.6$

and $\sigma_{b,nom,max}/R_{p0.02} = 0.31$. Fig. 5 shows that position of the dangerous stud's cross-section depends on helix position with respect to bending plane.

Fig. 6 indicates that the local stresses of the first turns determined for the stud M24×3.5 by the photoelastic method are less by 5.5% and 4.3% than stresses values in the stud M16×2 calculated using the presented analytical model. Calculations and experiment for eccentrically tensioned connection (Burguete and Patterson, 1994) were performed, when ratio of nominal stresses in the stud is $\sigma_{b,nom}/\ \sigma_{t,nom} = 0.48$.

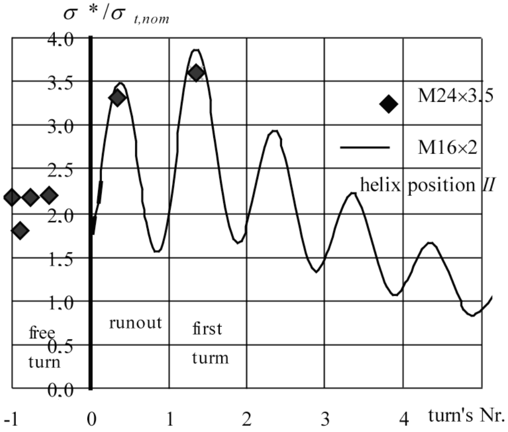


Fig. 6. Theoretical and experimental local stresses in stud's thread

The multi-segmental model of bent threaded connection. When threaded connection after tightening is only bent and bent for the first time, on one side from *NL* semi-turns load increases, and on the other side – decreases. Thus their pliability value on one side is γ_f , and on the other – γ_r. For this case the multi-segmental connection model is created (Fig. 7), where the semi-turns with pliability γ_f and γ_r alternately form the separate segments.

In case of this connection distribution, the same equations can be applied (9, 10) and (13, 14) to evaluate semi-turns loads and inner bending moments, which were derived for the three-segmental model.

By using multi-segmental model the calculation of the load distribution along thread of the threaded connection M16×2 have been performed. Calculation results are obtained for the case, when the threaded connection after tightening is only bent and bent for the first time. These results show that on one side from *NL* the summed load of semi-turns is less by approximately 6%, and on the other side it is less by 11% under comparison with the loads which affect the semi-turns in case of bending at the eccentric load of the connection, i.e. when pliability value of semi-turns on both connection sides γ_f is the same.

4. Durability of the Cyclically Bent Threaded Connections

The fourth chapter pays the main attention to determination of the cyclic parameters of turns load, inner bending moment and local stud's stresses, which values are necessary to perform stud's cyclic durability calculations. After the first loading cycle of the thread's turns, i.e. during the repeated loading cycles, the turns' deformation on both sides of the connection from the *NL* is determined by turns' pliability value γ_r. In this case the change of turns load and inner bending moments in the repeated cycle may be calculated applying the three-segmental model.

In Fig. 7 the three turns load amplitudes functions of the connection M16×2 are presented, when the nominal stud's stress is $\sigma_{b,nom,max}/R_{p0.02} = 0.31$: 1 – $u(z, \gamma_f, \gamma_f)$ – in case of the first bending semi-cycle of eccentric tension; 2 – $u_h(z, \gamma_f, \gamma_r)$, – in case of the first bending semi-cycle when the connection after tightening is only bent; 3 – $u_r(z, \gamma_r, \gamma_r)$ – for all cases of repeated bending cycle. The pliabilities, which the semi-turns present in the opposite connection sides A and B from the *NL* possess, are noted in the brackets of the indicated functions.

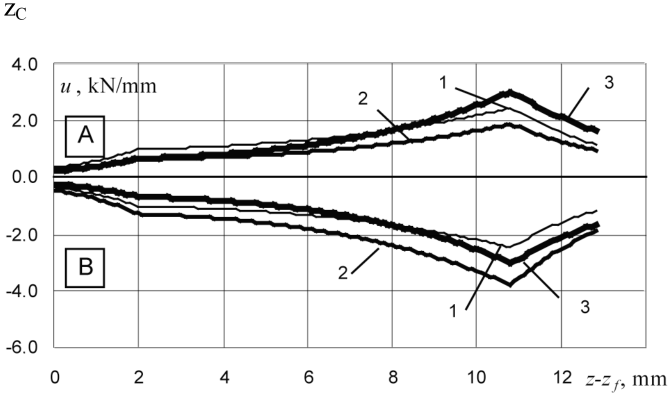


Fig. 7. The functions of turn loads amplitudes

After analysis of variations of turns load in the first and second loading cycle there was determined that the maximal values of turns load and inner bending moment for the repeated cycle shall be calculated according to the data of the first semi-cycle under condition of the greatest external bending moment.

This calculation is performed assessing turns pliability values, which semi-turns possess in both connection sides from the *NL*. Turns loads and inner bending moment amplitudes shall be calculated applying the same turns' pliability value γ_r for both sides of the connection.

Fatigue life prediction. In order to estimate fatigue life of the cyclically bent threaded connections the possibilities to apply strength calculation standard of the Russian Federation (RF standard 1989) and modified standard method are considered. Contrary to the standard method in its modification the data of stresses distribution along thread of the bent stud are used immediately.

Two Coffin-Manson-Langer type formulae are presented in standard. The smaller value of the number of load cycles up to crack initiation in the stud thread N_0 must be finally chosen out of two assessed values. The amplitude of alternating local stresses in thread roots of the stud $\sigma_a^* = K\sigma_{nom}$ for these formulae, is calculated by using only one stress concentration factor without separate estimation of the turns load and inner bending moment effects. The nominal stud's stress σ_{nom} is calculated by using values of the external axial and bending loads which differ from appropriate values of dangerous cross-section.

By using distribution of the stress $\sigma_a^*(z_i)$ in roots of the stud thread, defined under the methods presented in chapters 3 and 4, it is possible to calculate the number of cycles $N_0(z_i)$ until the crack appears for any turn of the stud, as well as $N_0(z_C)$ for the stud's dangerous cross-section at z_C thereof. Here expression $\sigma_a^*(z_C)$ obtained for studs at the thread helix position *I* was used. To prove this the following adjusted RF standard formula has been used:

$$\sigma_a^*(z_C) = \frac{E_{1s} e_c}{[4N_0(z_C)]^m} + \frac{R_c}{[4N_0(z_C)]^{\bar{m}_e} + \dfrac{1+r_c}{1-r_c}} \qquad (17)$$

where, E_{1s}, e_c, R_c, m, m_e, are material indexes, r_c is asymmetry factor.

The possibilities to apply RF standard formulas or modified standard formula (17) for cyclically bent threaded connection have been analyzed by using comparison of the calculated cycle life $N_{0,calc}$, with the experimental data $N_{0,exp}$. obtained aforetime in Laboratory of Strength of Mechanics, of Vilnius Gediminas Technical University. Cyclic life tests have been carried out under cyclic bending of the threaded connections M16×2 made from steel 25X1MФ.

The experimental values of crack initiation lifetimes of the studs $N_{0,exp}$ exceed lifetimes $N_{0,calc}$ calculated through the RF standard formulas about 2–15 times.

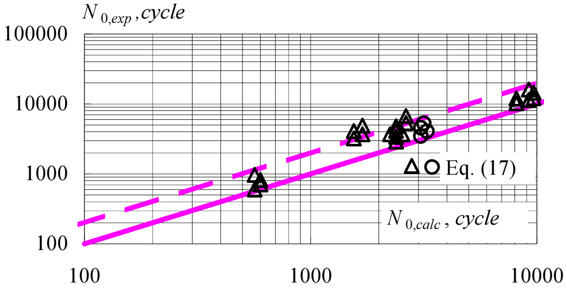


Fig. 8. Fatigue crack initiations in thread of stud M16×2

The low cycle durability up to 2×10^4 cycles of the cyclically bent threaded connections set according to modified method (17) for cyclic strength is notably higher (about 2–5 times) than the calculated values set according to the RF standard. They are close to experimental values, however do not exceed them (Fig. 8).

5. Increasing of the Cyclic Durability of the Threaded Connections

Positioning method. The first model presented in the fifth chapter for the fatigue life increasing is based on the equalization of an accumulative fatigue damages in the zone of the mostly loaded stud’s thread. The method can be realized by the periodical changes of the position of threaded connection with respect to bending plane. This possibility is examined by using the law of the load distribution in thread of bent threaded connection and the Miner’s linear damage summation principle. The durability of the stud bent cyclically through using of the positioning method can be increased up to 2 times till the occurrence of the crack.

The method of pre-overloading of threaded connection. According to this method a gaps in the thread must be formed by using plastic deformation of the turns. For this purpose only pre-overload of the threaded connection have to be performed during its tightening. Thereupon at the lower loading of the threaded connection the loads on the risky turns of the stud reduce. The legitimacy of the model is based on single turn pair unloading – reloading effect obtained experimentally. Using the pre-overloading of the connection, the maximal alternating local stresses in the thread of the stud can be decreased about 10–25%.

General Conclusions

1. Analysis of literature sources show that in low-cycle durability calculation of the bent threaded connections the local stresses in the thread of the stud are determined without assessment of load distribution in the turns of the thread and without analysis of the dangerous cross-segmental loading.

2. Pliability values γ_r of tested pairs of turns, which are determined while unloading and repeatedly reloading, are more than 2 times greater (approximately 2–2,4 times) than the pliability values γ_f of turns, which were determined according to the linear part of turns deformation curve during the first loading.

3. Created differential equations of compatibility of the elements displacements of the bent threaded connection relates the displacements of stud's core, nut's wall and pairs of the engaged turns.

4. Numerical values of solutions of differential equations – turn loads and inner bending moments, which are determined by analytical and *Runge – Kutta* methods, are slightly different throughout all the length of the threaded connection, but not more than 1%.

5. Created three-segmental model of the threaded connection is more rational mathematically than multi-segmental model to apply in cases of its eccentric loading or unloading, when semi-turn pairs have being in the opposite sides of the connection are deformed in the same direction – they are just loaded or unloaded. Multi-segmental model of the threaded connection is suitable to apply in the case of bending of the connection after its tightening, when in the first semi-cycle the semi-turns have being in the opposite sides of the connection are deformed in the oposite directions – they are loaded on the one side of the connection and unloaded on the other side.

6. Difference of maximal values of local stresses of the thread of the stud eccentrically loaded was determined by comparing of the results obtained by analytical model and photo-elasticity method (Burguete and Patterson, 1994) that makes up about 5%.

7. Low-cycle durability values of the bent threaded connections that are determined according to the modified standard formula applying the data of load distribution in the thread, are 2–5 times greater than durability values assessed according to the RF strength calculation standard. They are closer to the experimental durability values and do not exceed them.

8. Using periodic changes in the position of the threaded connection with respect to the bending plane, the durability of the stud bent cyclically can be increased up to 2 times till the occurrence of the crack. Using the pre-overloading of the connection, the maximal alternating local stresses in the thread of the stud can be decreased about 10–25%.

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CIKLIŠKAI LENKIAMŲ SRIEGINIŲ JUNGČIŲ DEFORMAVIMAS IR STIPRUMAS

Mokslo problemos aktualumas

Sriegines jungtys dažnai patiria ciklinių lenkimo apkrovų dėl temperatūros, vidaus slėgio ir jungiamųjų detalių deformacijų kitimo. Srieginėms jungtims, kurios patiria ašinių ciklinių apkrovų jau yra sukurtos modernesnės daugiaciklio ir mažaciklio ilgaamžiškumo skaičiavimo metodikos, kuriomis detaliai kiekybiškai įvertinamas ašinės apkrovos pasiskirstymas tarp vijų. Apkrovos pasiskirstymo sriegyje kiekybiniai duomenys leidžia detaliau ir tiksliau įvertinti konstrukcijos ypatumų (jungties ilgio, medžiagos, veržlės ir vijų formos) ir jungties elementų deformavimo stadijų įtaką.

Tokios ilgaamžiškumo skaičiavimo metodikos cikliškai lenkiamoms srieginėms jungtims netaikomos, nes lenkiamoms srieginėms jungtims nėra sukurtų apkrovos pasiskirstymo vijose analitinių modelių, tinkamų praktiniam naudojimui. Šioje srityje taip pat nėra sukurtų ir modelių, kurie skaičiuojami baigtinių elementų metodu.

Kadangi sriegin jungtis yra kompleksinis mazgas, kurį sudaro deformuojami elementai, tai apkrovos pasiskirstymą tarp vijų lemia jungties elementų deformacijų ir poslinkių suderinamumas. Matematiškai aprašant jungties deformuotą būvį, reikalingi teoriniai ir eksperimentiniai duomenys, kurie atspindėtų jungties elementų deformavimo specifinius ypatumus, pasireiškiančius veikiant lenkimui.

Disertacijoje siekiama sukurti cikliškai lenkiamų sriegini jungčių apkrovos pasiskirstymo sriegyje skaičiavimo metodą ir pritaikyti jį mažacikliam ilgaamžiškumui skaičiuoti.

Tyrimų objektas. Cikliškai lenkiamos sriegines jungtys.

Darbo tikslas ir uždaviniai. Lenkimo apkrovos pasiskirstymo sriegio vijose nustatymui sukurti cikliškai lenkiamos sriegines jungties modelius ir pritaikyti juos norminiam ciklinio ilgaamžiškumo skaičiavimui. Darbo tikslui pasiekti reikia spręsti šiuos uždavinius:

1. Eksperimentais nustatyti nukraunamų ir pakartotinai apkraunamų sriegio vijų porų paslankumo rodiklius.
2. Sudaryti lenkiamos sriegines jungties elementų tampraus deformavimo schemą ir vijų įlinkių, veržlės ir smeigės skerspjūvių kampinių poslinkių suderinamumą aprašančias diferencialines lygtis: a) kai sriegio vijos yra sukibusios visu profiliu, b) kai sriegio vijos yra sukibusios ne visu profiliu. Nustatyti diferencialinių lygčių apytikslius analitinius sprendinius ir patikrinti juos skaitiniais metodais.
3. Taikant diferencialinių lygčių analitinius sprendinius, sudaryti lenkimo apkrovos pasiskirstymo sriegio vijose modelius: a) trijų ruožų modelį necentriškai tempiamos jungties atvejui, b) daugiaruožį modelį atvejui, kai sriegin jungtis lenkiama po įveržimo.
4. Pritaikyti sudarytus apkrovos pasiskirstymo sriegio vijose modelius lenkiamų sriegini jungčių ciklinio ilgaamžiškumo (iki atsirandant plyšiui) norminiam skaičiavimui ir patikrinti skaičiavimo rezultatus remiantis eksperimentiniais duomenimis.
5. Pasiūlyti būdus sriegines jungties ilgaamžiškumui padidinti ir vietiniams įtempiams sumažinti pavojingoje sriegines jungties srityje. Sudaryti jų matematinius modelius.

Tyrimų metodai. Darbe taikomi analiziniai, skaitiniai ir eksperimentiniai tyrimų metodai.

Darbo mokslinis naujumas

1. Lenkiamos srieginės jungties deformavimui apibūdinti pasiūlyta originali deformavimo schema ir sudarytos vijų įlinkius su veržlės ir smeigės skerspjūvių kampiniais poslinkiais siejančios poslinkių suderinamumo diferencialinės lygtys: a) kai sriegio vijos yra sukibusios visu profiliu, b) kai sriegio vijos yra sukibusios ne visu profiliu.
2. Sudaryti lenkimo apkrovos pasiskirstymo srieginėje jungtyje modeliai: a) trijų ruožų necentriškai tempiamos sriegінės jungties modelis, b) daugiaruožis po įveržimo lenkiamos sriegінės jungties modelis.
3. Eksperimentais nustatyti pakartotinai apkraunamų sriegio vijų porų paslankumo rodikliai.
4. Sukurtas ciklinio ilgaamžiškumo padidinimo metodas, kuris įgyvendinamas periodiškai keičiant sriegінės jungties padėtį lenkimo plokštumos atžvilgiu. Sukurtas išankstinio perkrovimo metodas vietiniams įtempiams sumažinti smeigės sriegyje. Abiem metodams sudaryti matematiniai modeliai.

Darbo rezultatų praktinė vertė. Darbo rezultatai įgalina tiksliau įvertinti lenkimo apkrovos poveikį ir konstrukcinių veiksnių įtaką apkrovų pasiskirstymui sriegio vijose bei tiksliau prognozuoti lenkiamų sriegінių jungčių ciklinį ilgaamžiškumą. Jungties ir lenkimo plokštumos tarpusavio padėties periodinio keitimo metodas leidžia padidinti cikliškai lenkiamos sriegінės jungties ilgaamžiškumą.

Ginamieji teiginiai

1. Ženklus sriegio vijų poros paslankumo pokytis pasireiškia po pirmojo apkrovimo ją nukraunant ir pakartotinai apkraunant.
2. Sudaryti trijų ruožų ir daugiaruožis lenkiamos sriegінės jungties modeliai įvertina vijų sukibties nevientisumą ir vijų apkrovimo pobūdį – apkrovimą arba nukrovimą – necentriškai tempiamų ir po įveržimo lenkiamų jungčių atvejais. Modelių taikymas patikslina cikliškai lenkiamų sriegінių jungčių ilgaamžiškumo skaičiavimą.
3. Periodiški jungties padėties keitimai lenkimo plokštumos atžvilgiu padidina cikliškai lenkiamos sriegінės jungties ilgaamžiškumą. Išankstinis jungties perkrovimas sumažiną smeigės sriegio vietinius įtempius pavojingoje jungties srityje.

Disertacijos struktūra ir apimtis

Disertaciją sudaro: įvadas, penki skyriai, bendrosios išvados, literatūra ir šaltiniai, autoriaus publikacijų sąrašas ir trys priedai. Disertacijos apimtis yra 122 puslapiai, joje pateikta 64 paveikslai ir 8 lentelės. Disertacijoje panaudoti 86 literatūros šaltiniai.

Pirmas skyrius skirtas literatūrai apžvelgti. Jame apžvelgiama sunkiai apkrautų sriegininių jungčių taikymo sritis ir apkrovimo sąlygos, apžvelgiami ir analizuojami atlikti tyrimai, susiję su sriegininių jungčių cikliniu stiprumu.

Antrame skyriuje pateikti sriegio vijų poros deformavimo savybių eksperimentinio tyrimo rezultatai ir anksčiau literatūroje neminėtų nukraunamos ir pakartotinai apkraunamos vijų poros savybių analizė.

Trečiame skyriuje pateikta sriegines jungties elementų deformavimo schema, poslinkių suderinamumo diferencialinės lygtys, diferencialinių lygčių analitiniai sprendiniai ir lenkiamos sriegines jungties modeliai – trijų ruožų ir daugiaruožis tamprieji modeliai lenkimo apkrovos pasiskirstymui skaičiuoti.

Ketvirtame skyriuje nustatyti smeigės lenkimo įrąžos, vijų apkrovos bei vietinių įtempių ciklo parametrai. Palyginus skaičiavimo ir eksperimentinius rezultatus, patikrinta galimybė modifikuoto norminio mažaciklio ilgaamžiškumo skaičiavimo metodikoje taikyti lenkimo apkrovos pasiskirstymo sriegyje duomenis.

Penktame skyriuje pateikti du nauji sriegininių jungčių ciklinio ilgaamžiškumo padidinimo būdai ir jų matematiniai modeliai.

Bendrosios išvados

1. Literatūros šaltinių analizė rodo, kad skaičiuojant lenkiamų sriegininių jungčių mažaciklį ilgaamžiškumą vietiniai įtempiai smeigės sriegio įdubose nustatomi nevertinant apkrovos pasiskirstymo sriegio vijose ir neanalizuojant pavojingojo skerspjūvio apkrovimo.

2. Eksperimentinės vijų paslankumo γ_r reikšmės, nustatytos atlikus vienos vijų poros tempimo bandymus ją nukraunant ir kartotinai apkraunant, yra daugiau kaip 2 kartus didesnės (apytiksliai 2–2,4 karto) už vijų paslankumo γ_f reikšmes, nustatytas pagal pirmojo apkrovimo tiesinę vijų deformavimo diagramos dalį.

3. Sudarytos lenkiamos sriegines jungties elementų poslinkių suderinamumo diferencialinės lygtys susieja smeigės šerdies, veržlės sienelės ir sukibusių vijų porų poslinkius.

4. Diferencialinių lygčių sprendinių – vijų apkrovų ir vidinių lenkimo momentų – skaitinės reikšmės, nustatytos analitiniu ir Rungės – Kutto metodais visame srieginės jungties ilgyje, skiriasi nežymiai, ne daugiau kaip 1 %.

5. Sudarytas trijų ruožų srieginės jungties modelis yra matematiškai racionalesnis už daugiaruožį modelį, taikant juos ciklinio necentrinio tempimo atvejams, kai pusvijų, esančių priešingose jungties pusėse, apkrovimo pobūdis visuomet yra vienodas – jos apkraunamos arba nukraunamos. Daugiaruožis srieginės jungties modelis, sudarytas po įveržimo lenkiamų jungčių atvejui, įvertina skirtingą pusvijų, esančių priešingose nuo neutraliosios plokštumos jungties pusėse, apkrovimo pobūdį pirmajame pusciklyje, kai vienoje pusėje jos apkraunamos, o kitoje nukraunamos, ir vienodą šių pusvijų apkrovimo pobūdį pasikartojančiuose puscikliuose.

6. Lyginant necentriškai tempiamos smeigės sriegio maksimalių vietinių įtempių reikšmes, apskaičiuotas taikant sudarytą analitinį modelį su eksperimentinėmis reikšmėmis, gautomis fototamprumo metodu (Burguete ir Patterson, 1994), nustatytas šių reikšmių skirtumas sudaro apie 5 %.

7. Lenkiamų sriegінių jungčių mažaciklio ilgaamžiškumo reikšmės, apskaičiuotos pagal modifikuotą norminę formulę, taikant apkrovos pasiskirstymo sriegyje duomenis, yra 2–5 kartus didesnės už ilgaamžiškumo reikšmes, apskaičiuotas pagal normas (RF stiprumo skaičiavimo normos 1989). Jos yra artimesnės eksperimentinėms ilgaamžiškumo reikšmėms ir jų neviršija.

8. Periodiškai keičiant jungties padėtį lenkimo plokštumos atžvilgiu, cikliškai lenkiamos srieginės jungties ilgaamžiškumą iki plyšio atsiradimo galima padidinti iki 2 kartų. Taikant jungties išankstinį perkrovimą maksimalius sąlyginius vietinius įtempius smeigės sriegyje galima sumažinti apie 10–25 %.

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