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Experimental and analytical investigation of loosening and shakedown of the threaded joints

Mindaugas Leonavičius[a], Algimantas Krenevičius[a], Marijonas Šukšta[a]*, Stanislav Stupak[a] & Žilvinas Bazaras[b]
[a]Vilnius Gediminas Technical University, Department Strength of Materials, Sauletekio ave 11, LT-10223 Vilnius, Lithuania
[b]Kaunas University of Technology, Department of Transport Engineering, Kestucio st. 27, LT-44025 Kaunas, Lithuania

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In a tight threaded joint subjected to cyclic bending the regularities of crack formation and propagation possess specific features compared to joints subjected to the cyclic tension. The investigation results of tightening dependence on the number of cycles of threaded joints made of various steels show that a fatigue crack forms and propagates, plastic deformations develop or a structure element adapts oneself to a cyclic effect. In threaded joints subjected to tension and cyclic bending there is a link established between loosening and the fracturing process parameters such as the configuration and depth of crack. Due to such non-elastic deformation dangerous states may occur leading to deterioration of bolts. One of such states is characterised by a progressing accumulation of deformations resulting in the changes in the geometry of constructive elements. The approximate kinematic theorem has been used for the estimation of the bolt shakedown parameters in case of tension and bending.

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The analysis of developing the stress state and crack formation is presented by several researchers[1-8] which shows the resistance to cyclic disintegration, the complexity of adaptation process and regularities disclosed by experimental and theoretical research.

Threaded joints applied for connecting the covering of a high-pressure vessel and its body are calculated according to Russian Federation standards[9] (further marked as AEDS-atomic engineering design standards) and according to ASME Code[10,11] (further marked as ASME-the American Society of Mechanical Engineers boiler and pressure vessel code, an internationally recognised code). Calculation of important threaded joints is performed according to crack development. Evaluation of reliability and durability of joints is connected with the analysis of stresses and strains, with the investigations into kinetics of short cracks as well as in different factors stimulating or retarding this process. In reported studies[6], peculiarities of calculating threaded joint cyclic strength are analysed, the AEDS and the ASME code are compared.

An experimental and theoretical investigation[1-8] into the resistance of threaded joints to low cycle and high cycle loading proves that the existing calculation procedures are insufficiently justified. Therefore, on the basis the criteria of fracture mechanics and shakedown theories, the methods presented in this paper are specifying and improving with respect of design, technological and operational parameters. Some peculiarities of investigating and calculating threaded joints subjected to the tightening and cyclic bending are also presented. Overall dimensions of some structural elements are limited to general layout requirements. The loading level of joining elements as well as the effect exerted by adjacent members of a real structure may provoke the emergence of plastic strains. The fact that at the start of the loading procedure the accumulation of permanent strain due to plastic flow is no longer persistent after a certain number of cycles have been reached proves that the structure has already acquired a shakedown state with respect to such loads. Analysis of shakedown conditions may help to define the limit values of external loading parameters[5-6].

Experimental Procedure

The examination of the influence of a thread pitch on the deformation stability is carried out with the following joints: M48×5, M48×4 and M48×3. The thread profile of the screw is made rounded R=(0.12-0.144) P, when P is the pitch of the thread. The stud

*For correspondence (E-mail: marsu@fm.vtu.lt)

and the nut are manufactured of chromium steel (heat treatment method was normalizing). Chemical composition of chromium steel are (wt-%): 0.41 C, 0.28 Si, 0.55 Mn, 0.85 Cr, 0.03 S, 0.028 P. Mechanical properties of the steel were: yield stress σ_y=766-830 MPa; ultimate strength σ_u=1032-1050 MPa; reduction of area Z=47.4 – 50.9%.

Experimental examinations of the joint M48×4 of high temperature steel (oil hardening + tempering) are carried out under the influence of various prestress and variable bending at the room temperature. Chemical compositions of this steel are (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. Mechanical properties of the steel are: σ_y=930-1010 MPa; σ_u=1020-1050 MPa; Z=59-61%. Mechanical properties are determined for every stud.

The test was performed using the equipment, reading system of the turn and crack initiation of thread shown in Fig. 1. A pair of strain gages measures bending stresses within the stud. Another pair of strain gages is used for the control of the tightness force of the threaded joint. The resultant stress was considered as the relevant elastic occurring in case of plastic deformations. The tightness was decreasing when the cracks appeared and developed. The latter phenomenon can be result of crushing of the contacting surfaces of the stud-nut coupling, moving forward of the first turn of the joint, crushing of the supporting surface of the nuts and elongation of the stud-bolt.

With the purpose to ensure the reliability, the reference[2,9] contains the recommendation to enlarge the tightness up to 0.8 σ_y. While selecting the loading regime the reference was also made to the allowable stresses for bolts and studs according AEDS and the ASME. The initial prestress is regulated within the limits (0.55...0.75) σ_y and the resultant maximum stresses within the limits (0.915...1.2) σ_y.

Experimental examinations have shown that in some cases total of tensile and bending stresses reach a plastic range and penetrate to a certain depth. A further repeating load has an influence on the strength and reliability of connections. Decomposition, associated with the process of inelastic deformation, can be local or general one. The plastic deformations cause in the threaded joints, a progressive geometrical changes, redistribution of stretching efforts and decreasing of prestress. By slackening the stretch of jointing elements the leak-proof-ness can be broken in

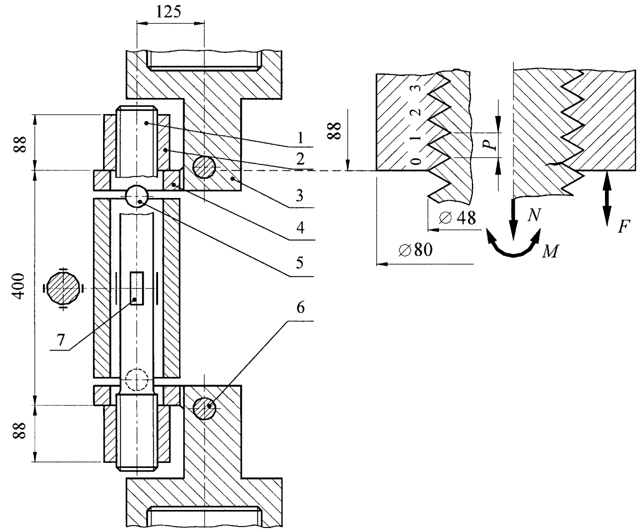

Fig. 1—Stud-nut bending equipment and stud-nut position (system of reading and crack initiation): (1) stud, (2) nut, (3) holder, (4) lever; (5) roller, (6) axis and (7) strain gage

the process of cyclic deformation. Initiation of crack was observed in notch of thread into plane of bending. The localized origin of the crack is related to the distribution of stresses among turns and the stress-strain state in the cavity between the turn 0 and 1. The increase of tightness and variable repeated loading of stud-nut system lead to the plastic deformation of certain zones of bolts. At beginning the crack appears in one side and later crack growth is varied. Crack may be on one side or on two sides of bolt.

Loosening

In order to achieve stable tightness of a threaded joint and at the same time, a stable prestress of connected elements, a multiple turn of the nut is mandatory irrespective of what type of threaded joint assembly method is used.

The investigation results of tightening dependence on the number of cycles of threaded joints with a different pitch M48×3, M48×4, M48×5 made of chromium steel are presented in Fig. 2a. In the tested joints tightening varied from σ_t=0.59σ_y to σ_t=0.82σ_y. Maximum stresses caused by bending varied from σ_b=0.38σ_y to σ_b= 0.43σ_y. Maximum stresses within the side layers varied from σ_{max}=0.98σ_y to σ_{max}=1.21σ_y. On the basis of the results obtained some generalisations can be made. At the same tightening value and with an increase in bending stresses, the longevity of studs decreases according to both threshold and a complete fracture. From the data presented in Fig. 2, one can draw a conclusion that

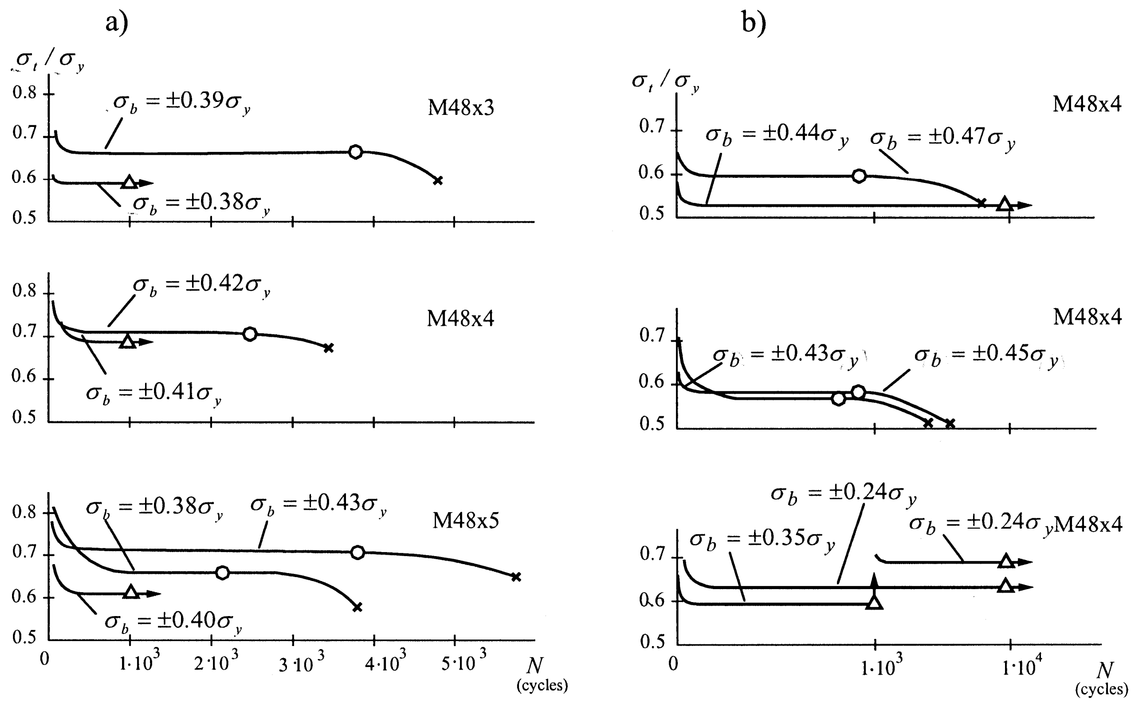

Fig. 2—Change in tightening of threaded joints made of chromium steel (a) and of high temperature steel (b): (O) threshold; (Δ)→ test is terminated; (x) full fracture, (↑) overprestress,

with an increase in the pitch of the tread from 3 mm to 5 mm, tightening during the first loading cycles decreases faster. No significant decrease in tightening was observed with the increase in the pitch during crack propagation.

The investigation results of tightening dependence on the number of cycles of threaded joints M48×4 made of high temperature steel are presented in Fig. 2b. In test joints tightening varied from σ_t=0.55σ_y to σ_t=0.715σ_y. Maximum stresses caused by bending varied from σ_b=0.235σ_y to σ_b=0.47σ_y. Maximum stresses within the side layers varied from σ_{max}=0.915σ_y to σ_{max}=1.14σ_y. Significant loosening (up to 16%) of the threaded joint would be observed at the beginning of cyclic bending. On the basis of the experimental data obtained the following conclusion can be drawn: provided the assembly is performed by a manifold turn of the nut, the tightening at the beginning of loading decreases not more than by 5% when $\sigma_{max} > \sigma_y$ and by about 3% when $\sigma_{max} < \sigma_y$. In threaded joints subject to stresses and cyclic bending there is a link established between loosening and the fracturing process parameters such as the configuration and depth of a crack. If crack appears and increase then threaded joint loss until 25% of initial tightness.

All the studs-bolts have been tested using the same device. For that reason the influence of the contacting surfaces of the side components of the equipment in principle is not possible. The decrease of the pressing force was not related to the elongation of the body of the stud.

Shakedown

In the physical sense the loosening and shakedown are interdependent whereas both these phenomena depend on the variable external loads and growth of plastic deformations. At the same time these investigations are not fully employed for stud-nut joints in the case of tension and bending. This problem is complicated in the case when the crack in the bolt arises. The new ideas of shakedown theory for structures with damages are presented elsewhere[12,13]. The principal derivations for solutions of shakedown problem for cracked bodies are proposed in these works. However, applying the results of these investigations for individual cases are very complicated. Requirements of the shakedown calculation are presented in standards of nuclear power plants designing[9], too. But these requirements usually are not applied for the design of threaded joints, shims and cotters. The special feature of this paper is that the kinematic shakedown theorem is applied for investigation of damaged bolt.

The shakedown conditions specified for such elements, the long-service life of which is determined by calculation of a relatively small number of load variation cycles may be used as a fracture criterion. Experimental investigation[5,6] into threaded joints has shown that in some instances total stresses arising due to tightening and cyclic bending efforts tend to reach the plastic area and even to penetrate to a certain depth. Also, it has been observed that following a low number of cycles and subsequent formation of a favourable field of residual stresses, cyclic plastic strains fail to accumulate, i.e., shakedown of joints take place. Violation of shakedown conditions may cause either an alternating plasticity (usually of a local character) or unlimited increase of plastic deformation affecting the structural element either in the whole or in a part of it.

The break view and the cross-section of the stud with a crack are shown in Fig. 3. Stud is affected by a constant axial force N and symmetric variable bending moment M ($-M^* \le M \le +M^*$). The way of solving of this problem may be the following. According to a possible nature of decomposition mechanism and specified distribution of shares the increments of strains are determined. Using the associated law of flow one can determine the proper stresses of a surface with a fictitious yield σ_{ij}^{0}. The equation of a fictitious surface[14] is:

$$\varphi(\sigma_{ij}^{0}) = \min_{\tau}\left[f(\sigma_{ij} - \sigma_{ij\tau}^{(e)})\Delta\varepsilon_{ij0}'' \right] = 0, \qquad \ldots (1)$$

where σ_{ij} are stresses on a real yield surface; $\sigma_{ij\tau}^{(e)}$ are stresses of applied external variable effects in an ideally elastic material. In the considered problem ($\sigma_{ij} = \sigma_z$) it is assumed that the decomposition mechanism is identical with an elongation of the stud:

$$\Delta u_{io}(x,y,z) = \Delta u_{zo} = const. \qquad \ldots (2)$$

Accordingly

$$\Delta\varepsilon_{ijo}'' = \Delta\varepsilon_{zo}'' = \frac{\Delta u_{zo}}{l}, \qquad \ldots (3)$$

where l is length of the stud (the distance between the loaded points of the nut-stud-nut joint); Δu_{io}, $\Delta\varepsilon_{ijo}''$ are elongation and strain of the stud.

Condition of a progressive variation of element configuration is:

$$N \cdot \Delta u_{zo} = \int_V \sigma_{ij*}^{o} \Delta\varepsilon_{ijo}'' \, dV = 4\int_0^l dz \int_0^{\frac{d}{2}} dx \times \int_0^{\sqrt{d^2/4 - x^2}} \left(\sigma_y - \frac{M}{I_x} y\right) \frac{\Delta u_{zo}}{l} dy. \qquad \ldots (4)$$

Introducing the dimensionless parameters $n = \frac{N}{N_y}$ and $m = \frac{M}{M_y}$ finally we receive an equation that characterizes the condition of one-sided accumulation of plastic deformations (unlimited increase of plastic deformations):

$$n + 0.72\, m = 1, \qquad \ldots (5)$$

where N_y is limit plastic axial force, M_y is limit plastic bending moment.

The condition of alternating plasticity is obtained by equalizing the double values of variable stress components to a yield stress:

$$2 \frac{M}{I_x} \frac{d}{2} = 2\sigma_y, \qquad \ldots (6)$$

where d is diameter of stud and I_x is moment of inertia.

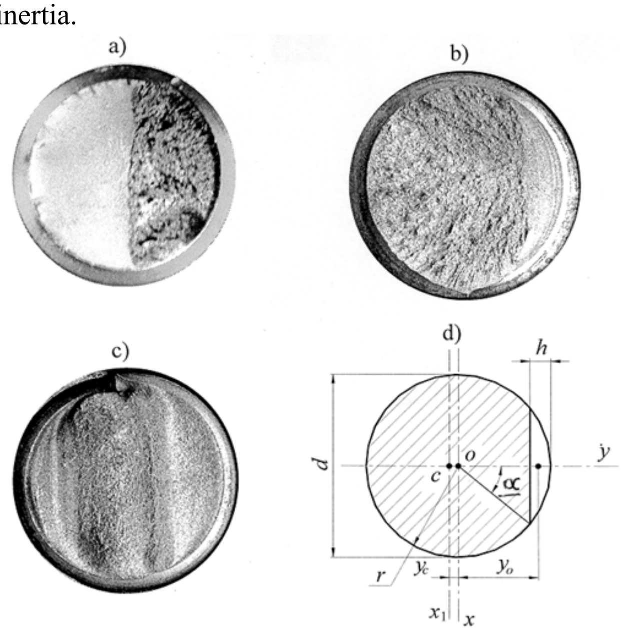

Fig. 3—The breaks view of a stud-bolt with crack: (a) and (b) crack is on one side of stud; (c) crack is on two side of stud; (d) model of cross-section

Introducing the dimensionless parameters of the bending moment m, we receive from Eq. (6):

$$1.70\, m = 1. \qquad \dots (7)$$

The state of undamaged threaded joints is shown on the diagram of shakedown, Fig. 4. The line 1 corresponds to the conditions of an alternating plastic flow according to the Eq. (7). The line 2 corresponds to the condition of unlimited accumulation of plastic deformations [Eq. (5)]. As it is obvious, all the points related to the tested stud are in the range of the lines 1 and 2.

The Eqs (5) and (7) are applied for undamaged cross-section of stud. When there is a crack in on side of cross-section, then by assuming an perfectly elasticity the components of variable stresses are calculated according to the following equation:

$$\sigma_z^{(e)} = \frac{M}{I_{x1}}\left(y + y_c\right), \qquad -r\cos\alpha \le y \le r\cos\alpha, \quad \dots (8)$$

The condition of incremental collapse or cumulative plastic deformations is:

$$N \cdot \Delta u_{zo} = 4\int_0^{l_o} dz \int_0^{r\cdot\cos\alpha} dy \int_0^{\sqrt{r^2-y^2}} \times\left[\sigma_y - \frac{M}{I_{x1}}\left(y + y_c\right)\right]\frac{\Delta u_{zo}}{l}\, dx. \qquad \dots (9)$$

From here it is obtained:

$$N + \frac{4M}{I_{x1}}\left[\frac{r^4}{3}\left(1-\sin^3\alpha\right) + \frac{r^2 y_c}{2}\left(\frac{\pi}{2} + \frac{1}{2}\sin 2\alpha - \alpha\right)\right] = \sigma_y r^2\left(\pi \sin 2\alpha - 2\alpha\right). \qquad \dots (10)$$

where y_c is position of the centroid of the cross-section when cracks appear; I_{x1} is the moment of inertia about axis x_1 (Fig. 3).

After corresponding marking n and m are brought into this expression, finally we receive:

$$\frac{\pi}{\pi + \sin 2\alpha - 2\alpha} n + \frac{16 r^4}{3 I_{x1}} \times\left[\frac{1}{6}\frac{\sin^3\alpha}{\left(\pi - \alpha + \sin\alpha\cdot\cos\alpha\right)} + \frac{1}{3}\frac{1-\sin^3\alpha}{\left(\pi + \sin 2\alpha - 2\alpha\right)}\right] m = 1. \qquad \dots (11)$$

In order to examine the dependence of the shakedown zone upon the crack depth, let us introduce the factor coefficient $k=h/r$ (Fig. 3). Then it is obtained:

$$k=0; \qquad 1.000\, n + 0.720\, m = 1; \qquad \dots (12)$$

$$k=0.10; \qquad 1.040\, n + 0.768\, m = 1; \qquad \dots (13)$$

The condition of alternating plasticity for cross-section with crack is:

$$1.82\, m = 1. \qquad \dots (14)$$

The state of threaded joints with crack is shown on the diagram of shakedown, Fig. 5. The line 1 corresponds to Eq. (14) and line 2 corresponds to Eq. (13).

Figures 4 and 5 show that influence of materials and pith of a stud on shakedown are small.

The received data enable to identify the reserve according to the shakedown diagram and the radius of similar cycles. By using the Eqs (12) and (13), the factor of safety can be defined as follows:

$$\eta = \frac{1}{a \cdot n + b \cdot m} \qquad \dots (15)$$

where a, b are the coefficients of Eqs (12) or (13).

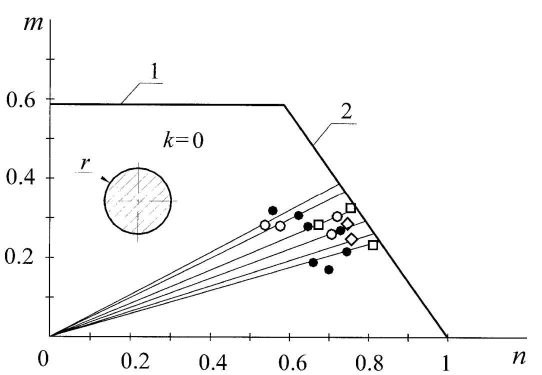

Fig. 4—Diagram of shakedown of studs without crack: (O) M48×3; (◘) M48×4; (□) M48×5 (chromium steel); (●) M48×4 (high temperature steel)

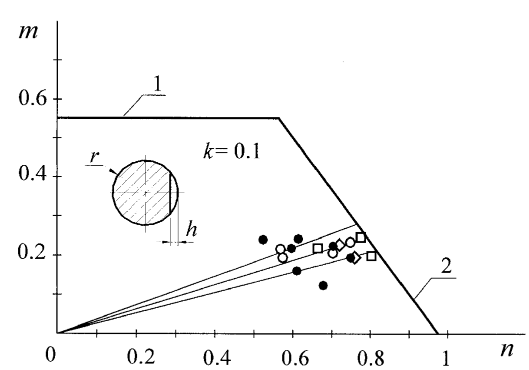

Fig. 5—Diagram of shakedown of studs with crack: (O) M48×3; (◘) M48×4; (□) M48×5 (chromium steel); (●) M48×4 (high temperature steel)

For the experimentally tested joints the factor of safety was found to vary within 1.06 and 1.79.

Given the tightening effort is close to $0.8\sigma_y$ and bending effort is $0.4\sigma_y$, the factors of safety for the progressive configuration variations are close to 1. It is estimated that such factors of safety in the elastoplastic area are insufficiently reliable. Therefore, improvement of methods related to evaluating cyclic strength and shakedown is very urgent, since it will help increase the reliability of objects in the design.

Conclusions

From this study the following conclusions can be drawn:

(i) Experimental studies have shown that the initiation and propagation of cracks have specific features which are characteristics only of threaded joints. It may be one-sided or two-sided caused by the action of stretching force and variable bending moment of symmetric cycle.

(ii) The investigation of threaded joint loosening mechanisms shows that this process depends on the prestress and crack propagation. Significant loosening (up to 16%) of the threaded joint would be observed at the beginning of cyclic bending. When crack increase then threaded joint loss until 25% of initial tightness.

(iii) Experimental examinations have shown that in some cases total stretching and bending stresses reach plastic range and penetrate to a certain depth. The threaded joints as far as possible adapt themselves to circumstances. The kinematic shakedown theorem is used for the analysis of bolts stress state.

(iv) The analytical relationships of plastic failure and a progressive profile change that were derived for crack-free studs, and with allowance for such fracturing process parameters as the profile and depth of a crack and the reduction of tightening. The condition of a progressive profile change may be used as a limit state occurring in the marginal layers of a stud in case the sum of tensile and bending stresses is close to $1.2\sigma_y$. When this state is exceeded, accumulation of unidirectional plastic deformations follows.

(v) If the factors of safety for the shakedown are close to 1 it is insufficiently reliable. In order to develop a uniform cyclic strength and shakedown calculation procedure for critical threaded joints, a new calculation of a progressive profile change is recommended to be performed before the calculation of cyclic strength.

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