Assessment of the load-loading capacity of bolted joints during bolt bending and the combination of materials used

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Abstract*:* based on the physical model of a hinged-bolt joint, which takes into account the possible bending of the bolt and, consequently, the real nature of the distribution of contact loads, the influence of the main design parameters of the joints on the distribution of loads between individual elements depending on the combination of their materials is analyzed. Dependencies for determining normal stresses in a given section of a connection element are presented, variants of the structural and technological design of typical hinge-bolt connections are analyzed according to the degree of influence of their geometric and material science features on the level of contact loads.

1 Introduction

When calculating a hinge-bolt connection for strength and durability, it is necessary to take into account the actual loading of each individual element. When the connection is in operation, force is transferred from one element to another through a distributed load at the points of contact between the eye and the bolt. Simplified schemes, in which this contact load is assumed to be uniformly distributed, can produce significant errors, especially as the length of the bolt increases and its rigidity decreases. However, in the overwhelming majority of the proposed calculation methods, fairly "thin" hinge-bolt joints are considered with the assumption of uniform distribution of stresses from the external load in the eyes and forks, that is, without taking into account the bending of the bolt [1-4]. This assumption significantly simplifies the strength calculation, but leads to some errors, which increase with increasing bolt length for fairly wide hinge-bolt joints. Strengthened circuits are successfully used in design calculations, which meets the requirements of the primary design stage [5,6]. In real connections, due to the bending of the bolt and uneven deformation of the contacting parts of the lugs, a redistribution of the contact load occurs, which leads to a decrease in the maximum bending stresses in the bolt and at the same time to an increase in the maximum contact stresses between the bolt and the joined elements. Therefore, the most accurate results are achieved when using calculation schemes that take into account the actual bending of the bolt and the resulting redistribution of the contact

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load in the connection elements [7].

2 Materials and Methods

A fairly accurate and complete model of a hinge-bolt connection for engineering calculations was proposed by V.I. Ryabkov [8,9]. A generalized physical model of a typical connection in which the central eye and fork are connected by a composite bolt is shown in Fig. 1. The model assumes loading of a connection, generally asymmetrical about the Y axis, with a force P and a moment M. A composite bolt consists of an external hollow bolt and an internal tie, which, being in a stretched state, compresses the hollow power bolt with a force T. It should be noted that The inner wall can also be made hollow to facilitate connection. The model takes into account the characteristics of the materials of the eye and bolt, the geometry of the eyes, determined by the ratio of the parameters d_b/D, the gap between the eye and the bolt, the roughness of the contact surfaces, their defects in the form of ledges, taper, ovality associated with technological errors and operational wear. It is possible to take into account the additional bending moment of the bolt head and nut.

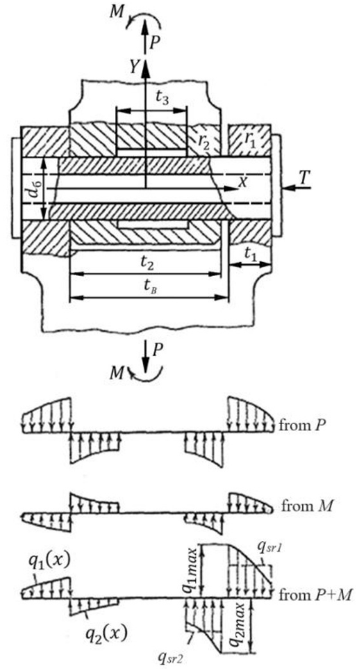


Fig. 1. Generalized physical model of a typical hinge-bolt joint and the nature of the distribution of contact loads

When determining the stress-strain state of the hinge joint elements, the problem is solved in the area of elastic bending stress of a bolt, like a beam supported on an elastic base. In the area of contact between the lugs and the bolt, the bolt is considered absolutely rigid and it is assumed that deformation occurs only due to the collapse of the lug. In this case, it is considered that between the linear load $q(x)$, acting along the contact line of the eye and bolt, and a function characterizing the elastic deformation of the eyes $v(x)$, there is a connection

$$q_i(x) = -G_i(x, N)v_i(x), \tag{1}$$

where $G_i(x, N)$ – the coefficient of elastic interaction of the elements of the hinge joint, which takes into account the properties of the material, the state of the contact surfaces, the fit of the bolt and some other factors; this coefficient under cyclic loading can change as a result of wear, changes in the gap and the condition of the contact surfaces; $i = 1, 2$ – numbers of contact areas (1 – refers to the outer eyes forming the fork; 2 – to the middle eye).

In general, the function$v_i(x)$ looks like

$$v_i(x) = l_i + \theta_{ix} + y(x) - \psi_i(x, N), \tag{2}$$

where $y(x)$ – unknown deflection function of the neutral axis of the bolt; $\psi_i(x, N)$ – a function characterizing technological and operational deviations along the line of contact of elements (ledges, irregularities from machining, ovality, etc.); l_i, θ_{ix} – respectively, linear and angular movements of one of the eyes under the influence of force and moment (Fig. 2).

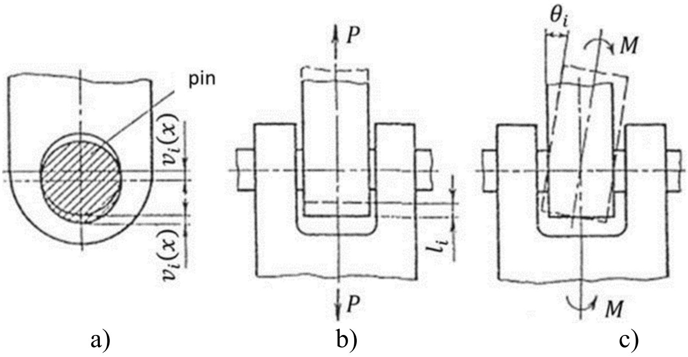


Fig. 2. Explanation of the parameters of the hinge joint model: a – elastic deformation of the eyelet$v_i(x)$; b – linear movement of the eyel_i under force$P$; c – angular movement (angle of rotation) of the eye θ_i under the influence of the moment M

The equation of an elastically compressed bolt lying on an elastic base is given in the form of a differential equation [2]:

$$(\chi(x)y'')'' + Ty'' - G_1(x)\big(y(x) - \psi_1(x)\big) = q(x), \tag{3}$$

where $\chi(x) = EI(x)$ – flexural stiffness of the bolt, which in general can be variable along its length; T – longitudinal force applied to a bolt when tightening the inner shank (for composite bolts $T > 0$; for whole – $T = 0$); quantities $G_1(x)$ and $\psi_1(x)$ explained above (the index "1" indicates that it belongs to the outer eyes that form the fork); $q(x)$ – distributed load along the bolt due to the impact of the lugs.

3 Research and results

Using mathematical transformations and value substitution $q(x)$ from expression (3) we obtain:

$$\frac{d^2}{dx^2}\left(\chi\frac{d^2y}{dx^2}\right) + T\frac{d^2y}{dx^2} + G_1y + G_2y + \frac{G_2}{rt - \rho^2} \times$$

$$\times \int_{r_2} G_2 y dx\, [\chi S - t] + \frac{G_2}{2t - S^2} \int_{r_2} G_2 y dx\, [S - rx] =$$

$$= G_1\psi_1 + G_2\psi_2 - \frac{G_2}{rt - S^2}[R_1 t - R_2 S + R_2 rx - R_1 Sx], \tag{4}$$

where,

$$r = \int_{r_2} G_2 dx; \qquad S = \int_{r_2} G_2 x dx; \qquad t = \int_{r_2} G_2 x^2 dx\,;$$

$$R_1 = P + \int_{r_2} G_2\psi_2 dx\,; \qquad R_2 = M + \int_{r_2} G_2\psi_2 x dx.$$

Expression (4) together with the boundary condition at the ends of the bolt

$$\left[\frac{d}{dx}\left(\chi\frac{d^2y}{dx^2}\right)\right]_{\substack{x=l_l\\ x=l_p}} + T\frac{\left[y(-l_l) \pm y(l_p)\right]}{l} = 0 \tag{5}$$

is a boundary value problem, the solution of which in the form of a linear combination of coordinate functions allows us to determine the deflection function of the neutral axis of the bolt $y(x)$. In expression (4) G_1 and G_2 – combined segments on which contact between the bolt and the eyes occurs (these segments determine the type of function $\psi(x)$; l_l and l_p – distance from the origin to the outer edges of the left and right fork lugs [10].

Using the solution to the boundary value problem specified by equations (4) and (5), the function is determined by formula (2) $v_i(x)$ and according to formula (1) – the desired expression of the function $q_i(x)$, those. diagram of the loads acting in the contact zones on the lugs and the bolt. As a result, it seems possible to determine the normal stresses in the design sections of all the main elements of the hinge-bolt connection [11].

Based on the above methodology, it is possible to analyze the influence of the main design parameters of hinge joints (dimensions D and t lugs and forks, bolt diameter d_b, the degree of hollowness of the bolt, etc.), the size of the gap, the characteristics of the materials used, the presence of bushings made of different materials, the tightening of the bolt in the connection, the nature of its loading (symmetrical, obliquely symmetrical, combined) and some other factors on the distribution of loads between individual elements along the thickness of the lugs and bolt length. It is convenient to carry out such an analysis using the coefficients of structural stress irregularity. In engineering calculations of lugs, its value can be determined by the formula

$$K_k(x) = K_{sr}K_r, \tag{6}$$

where $K_{sr} = q_i(x)/q_{sri}$ – coefficient of unevenness of distributed load along the length of the bolt (it is assumed that the outer diameter of the bolt is constant along the entire length of the contact) or along the thickness of the eye ($q_i(x)$ – distributed contact load; for outer lugs thickness t_1 forming a fork, $q_{sr1} = P/2t_1$; for medium eye thickness t_2, $q_{sr2} = P/2t_2$); K_r – coefficient taking into account the influence of eye geometry on the breaking load [12].

Coefficient value K_r depends on the properties of the eyelet material and its geometric parameters D/d *and* $c = a/b$. It is determined on the basis of massive experimental studies of the static strength of lugs.

If the parameters $D/d = 2 \dots 3$ and $a/b = 1 \dots 1{,}4$, then the influence of the geometry of the lugs and the properties of the material on the coefficient K_r is small, and its value can be determined using the approximate formula

$$K_r = 0{,}56 + 0{,}46\,a/b - 0{,}1\,D/d. \quad (7)$$

Based on the known value of the coefficient of structural stress irregularity $K_к$ it is possible to determine the normal stresses in a given section of a specific connection element. The magnitude of longitudinal normal stresses for bolts can be calculated using the formula

$$\sigma_{izg}(x) = K_k(x)\frac{P}{P_r}\sigma_v. \quad (8)$$

For hinged joints with two cut planes, this formula can be converted to the form

$$\sigma_{izg}(x) = K_k(x)\frac{2P}{\pi d_b^2}\frac{\sigma_v}{\tau_v}, \quad (9)$$

where τ_v – shear strength of bolt material.

An analysis of various design and technological options for standard hinge-bolt joints showed that the main influence on the level of contact stresses between the lugs and bolts is exerted by the following factors: the relative thickness of the lugs t_1/d_b, t_2/d_b; ratio of elastic interaction coefficients between single lugs and fork lugs G_1/G_2; bending stiffness of a bolt (in the general case of a composite) $\chi(x) = EI(x)$; bolt hollowness degree m; the magnitude of the axial force of the bolt pre-tensioner T; geometry deviations and roughness of contact surfaces determined by the function$\psi(x, N)$; type of external load, etc. [13-15].

Let us consider a number of specific examples of the influence of design factors on the distribution and magnitude of normal stresses in the eyes and bolts of hinged joints, widely used in aircraft structures.

Influence of attitude t_2/d_b (where t_2 – thickness of the central eye) by the value of the coefficient K_k with different lengths of the hollow section in the eyelet t_3 (see Fig. 1) is shown in Fig. 3. The largest value of the coefficient K_k corresponds to the values t_2/d_b from 1 to 3, which are often found in bolted joints. With an increase in the hollow section in the eyelet, the value K_k decreases without reducing its strength.

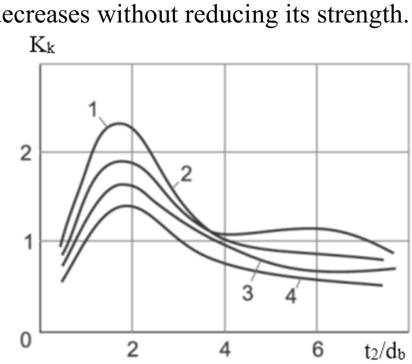
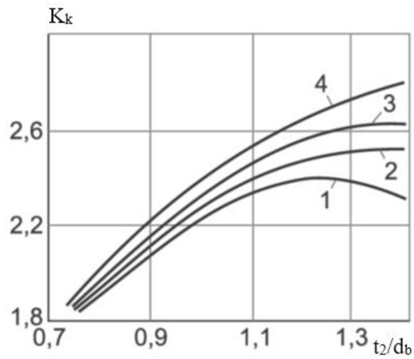
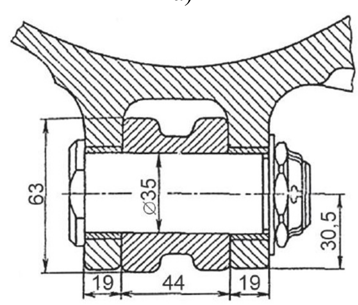


Fig. 3. Dependencies of the coefficient K_k on the relative thickness of the central eye t_2/d_b hinge joint loaded with tensile force, for different lengths of the hollow section in the eye t_3/t_2: 1 – 0; 2 – 0,4; 3 – 0,6; 4 – 0,8

The influence of the material in the manufacture of the eye or fork on the value of the coefficient $K_к$ shown in Fig. 4. Calculations were carried out for the hinge-bolt connection of the side strut with the shock absorber cylinder of the aircraft landing gear, loaded with tensile force, with the ratio of the eye parameters $2t_1/t_2 = 1$ and $t_3 = 0$. Graphs in Fig. 5, but built on the maximum values K_k, which, with different combinations of materials used, can be located in different sections of the connection. As follows from the data presented, when manufacturing an eye or snare by replacing steel with a titanium alloy, the coefficient increases by reducing the rigidity of individual elements of the connection K_k, and consequently, the irregularity of stress increases [16-18].



a)



№ positions	Material	
	eyelets	forks
1	steel	steel
2	titanium	steel
3	steel	titanium
4	titanium	titanium

b)

Fig. 4. Dependencies of the coefficient K_k, on the relative thickness of the eyelet t_2/d_b: a – in the manufacture of lugs and forks from various materials; b – for the hinge-bolt connection of the strut with the shock absorber cylinder of the aircraft landing gear

In Fig. Figure 5 shows the effect of two relative connection parameters $2t_1/t_2$ and t_2/d_b by the coefficient K_k at$t_3 = 0$ for the case where all the eyes and bolt are made of steel.

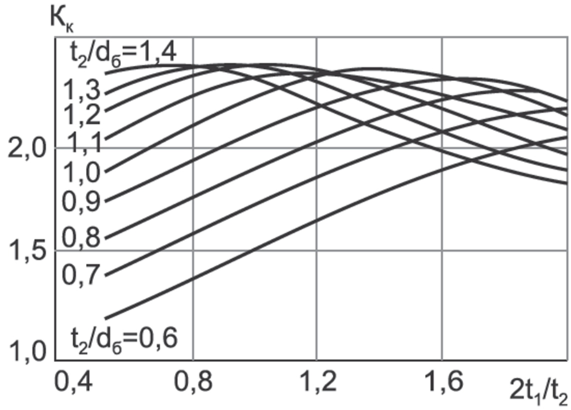


Fig. 5. Dependence of the coefficient K_k on the ratio of the thickness of the lugs $2t_1/t_2$ at different values of the relative thickness of the central eye t_2/d_b for articulated connections with steel elements subject to tensile forces

Effect of Bolt Hollowness m the coefficient of irregularity of bolt bending stress is shown in Fig. 6. Calculations were made for a hinge-bolt joint loaded with tensile force, for a cross section of the bolt in the plane of symmetry of the connection.

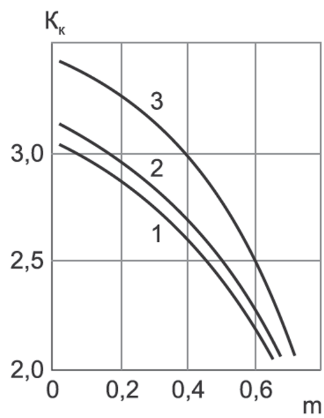


Fig. 6. Dependences of the coefficient of structural stress irregularity K_b on the degree of hollowness of the bolt m for a swivel joint having eyes with the parameter $t_2/d_b = 2{,}0$ and different ratio values d/D: 1 – 0,5; 2 – 0,6; 3 – 0,7

A change in the hollowness of a bolt is associated with a change in the location of the material relative to the axis of the bolt. As m increases, the moment of inertia of the bolt cross-section increases; for the same cross-sectional area, its rigidity increases EI bending, which leads to a decrease in the coefficient K_k and, consequently, to a decrease in stress irregularity [19,20].

To assess the accuracy of the proposed method for determining contact loads and stresses in the elements of hinged joints, a comparison of the calculation results using this method with the results of experimental studies and calculations carried out according to a simplified scheme, which assumes fastening the bolt at four points of support, is shown (Fig. 7). As can be seen from the given diagrams of bolt bending stresses, the proposed method allows us to fairly accurately assess the nature of the stress state along the entire length of the bolt. The error of calculations relative to experimental data does not exceed 20%.

4 Conclusion

The basis for selecting specific parameters of a hinged-bolt joint according to the durability criterion is the ratio:

$$K_k \leq K_k(N_{OTK}), \tag{10}$$

where $K_k(N_{OTK})$ – the maximum permissible value of the coefficient of structural stress irregularity, determined by the nature of the variable load, the fatigue resistance characteristics of materials and, in some cases, design parameters; N_{OTK} – durability of the connection element until it fails.

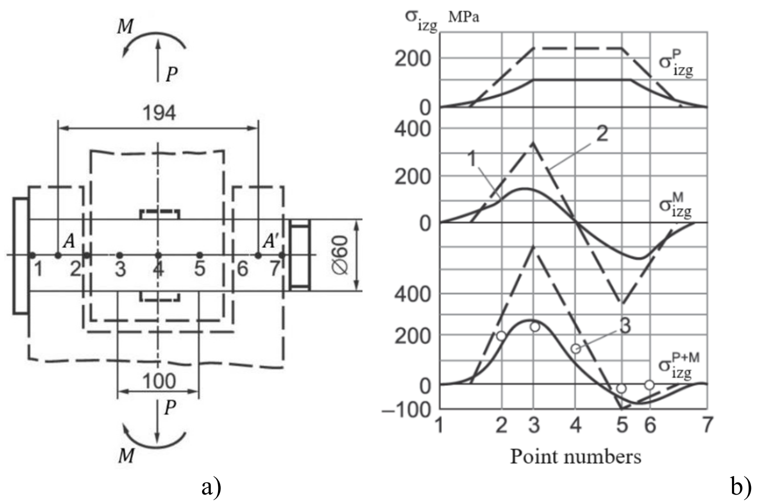


Fig. 7. Distribution of bending stresses along the length of the bolt with Ø60 mm from steel 30KhGSA at $P = 163\,000$ N and $M = 21\,400$ N·m: 1 – calculation results using the proposed method; 2 – results of calculation according to the diagram (bolt on four supports at points *A*, 3, 5, *A′*); 3 – experimental data

Thus, the choice of the main parameters of a hinge-bolt connection represents a process of comparing the value $K_k(N_{OTK})$ with meanings K_k, which can be calculated in advance and presented in the form of tables or a data bank.

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