MODELLING NONLINEAR MULTI-BOLTED CONNECTIONS: A CASE OF THE ASSEMBLY CONDITION

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Abstract. The article deals with modelling and calculations of asymmetrical multi-bolted connections at the assembly stage. The physical model of the joint is based on a flexible flange element that is connected with a rigid support by means of the spider bolt models. Between the joined elements the nonlinear Winkler model of a contact layer is taken into consideration. A computational model of the system is proposed, which makes it possible to analyze how the tightening sequence affects the distribution of preload both during the multi-bolted connection assembly and after it has been completed. The sample results obtained from the calculations are presented.

Keywords: multi-bolted connection, FE-modelling, preload.

Introduction

Multi-bolted connections used in mechanical engineering (also for applications in agriculture engineering) are commonly designed as preloaded joints. In traditional methods of calculations [1; 2], the assembly state of multi-bolted connections is usually excluded. Instead of this, equal load of all the bolts and uniform contact pressure between the joined elements after the preloading process are assumed. However, the final tension of the joint at the end of its assembly operation depends on both the assumed sequence of bolt tightening [3; 4] and the way of bolt tightening [5; 6]. Due to this the contact pressure distribution between the joined elements is irregular. Additionally, influence on it may also have the following factors:

- flange imperfections [7; 8];
- surface texture of the joined elements [9];
- cyclic loading of the connection [10];
- flange and bolt creep under elevated temperature conditions [11];
- incorrect value of the preload [12; 13];
- specificity of the way of creating the connection, through which the greatest load contact surfaces of the joined elements occurs around the bolt head [14-16].

All these phenomena cause that the comprehensive solution of problems occurring in multi-bolted connections has not yet been carried out and the task of modelling multi-bolted connections is still valid and important.

In the previous paper [3] some results of theoretical investigations for the preloading process of an asymmetrical multi-bolted connection, composed of a flange element fastened to a rigid support, were released. In the proposed model the joint bolts were treated as rigid body bolt elements consisting of a flexible plain part of the bolt and a rigid bolt head [17]. In the current paper some new results of modelling the preloading process of an analogical model of the joint are presented. In the new model, bolts are treated as spider bolt elements [17]. For modelling and calculations of the multi-bolted connection the finite element method (FEM) [18] is used.

In this paper the first stage of modelling and calculations of multi-bolted connections is presented, which is related to the case of the assembly condition. The second stage, which is associated with the case of the operational condition, is shown in [19].

Materials and methods

A general structure of the multi-bolted connection model results from an idea presented in the article [3]. The model of the joint can be found in Figure 1. It is based on a flexible flange element that is fastened to a rigid support by means of k spider bolt elements [17], which substitute bolts. Spring properties of the i-th model of the bolt (for $i = 1, 2, \ldots, k$) are determined from the relation:

$$c_{yi} = \frac{1}{\sum_{n} \frac{1}{c_n}}, \tag{1}$$

where c_{yi} – stiffness coefficient of the bolt, N·mm^{-1};
c_n – stiffness coefficient of the n-th bolt fragment, N·mm^{-1}.

Multi-bolted connections are most commonly used to join a pair of elements. Since the surface texture of structural elements is irregular [15; 20], in the case of combining them, between the elements the nonlinear contact model should be introduced. In the present model of the multi-bolted connection the contact joint is modeled as the nonlinear Winkler model, which is described by means of l one-sided nonlinear spring elements, defined by the following relationship:

$$R_j = A_j \cdot f(u_j), \tag{2}$$

where R_j – force in the centre of the j-th elementary contact area (for j = 1, 2, …, l), kN;
A_j – j-th elementary contact area, mm^2;
u_j – deformation of the j-th nonlinear spring element, µm.

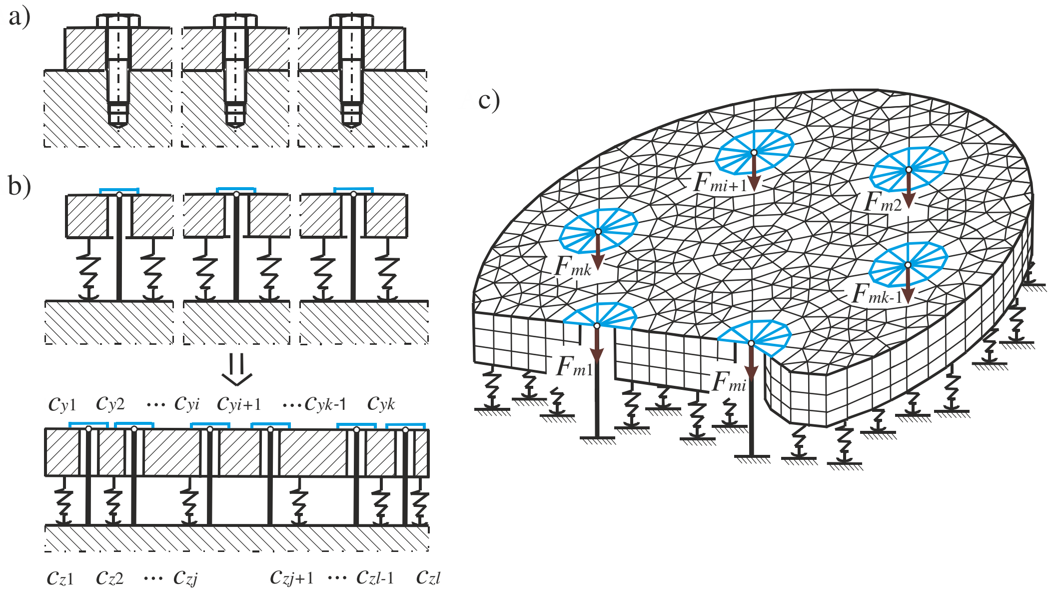

Fig. 1. **Multi-bolted connection:** a – scheme; b – description of spring properties; c – FEM-model with spider bolt models

The equation of system equilibrium can be written in the form:

$$K \cdot q = p, \tag{3}$$

where K – stiffness matrix;
q – displacement vector;
p – load vector.

The following three different subsystems in the discussed multi-bolted connection can be adopted:

- subsystem B, composed of the bolts;
- subsystem F, which is the flexible flange element;
- subsystem C, associated with the conventional contact layer.

In the assembly condition, the load vector p is composed of preloads F_{mi}, as shown in Figure 1c, and the displacement vector q is described using the following formula:

$$q = col(q_B, q_F, q_C), \tag{4}$$

where q_B – displacement vector of bolts;

q_F – displacement vector of the flexible flange element;
q_C – displacement vector of nonlinear springs.

Therefore, the equation (3) can be written as:

$$\begin{bmatrix} K_{BB} & K_{BF} & 0 \\ K_{FB} & K_{FF} & K_{FC} \\ 0 & K_{CF} & K_{CC} \end{bmatrix} \cdot \begin{bmatrix} q_B \\ q_F \\ q_C \end{bmatrix} = p, \tag{5}$$

where K_{BB}, K_{FF}, K_{CC} – stiffness matrices of subsystems B, F, C;
K_{BF}, K_{FB}, K_{FC}, K_{CF} – matrices of elastic couplings among subsystems B, F, C.

On the basis of this model of the multi-bolted connection, bolt forces both during the joint assembly and after it has been completed can be evaluated.

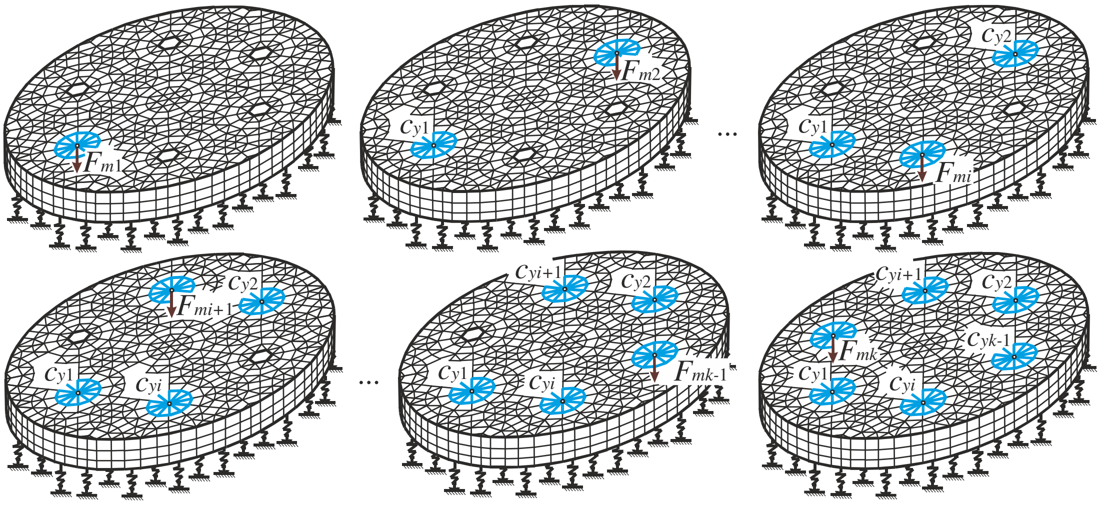

Fig. 2. **Preloading process of the multi-bolted connection**

The scheme of the preloading process of the connection is given in Figure 2. It consists of k steps, according to the number of bolts in the joint. During the first bolt tightening, the system is composed of a flange element resting on a nonlinear elastic foundation and clamping by only one bolt. Thus, the system is loaded by the force F_{m1}, which is the preload of the bolt No. 1. In this first step, as a result of solving the equation (5), one obtains, among others, the displacement vector of nonlinear springs $\boldsymbol{q}_C$, which defines initial deformation of these springs in the second step of joint tightening:

$$q_C = col(q_{C1}, q_{C2}, \ldots, q_{Cj}, \ldots, q_{Cl}). \tag{6}$$

In the next steps of joint tightening (for $i = 2, \ldots, k$), the next spider bolt model is taken into consideration. Simultaneously, in the equation (5) the stiffness matrix of the bolts subsystem K_{BB} is complemented by the elements, which are preloaded in the analyzed step of computations. Each time, in the current step of joint tightening, the stiffness matrix of the bolts subsystem K_{BB} is a constant part of the stiffness matrix K, and the stiffness matrix K_{CC} is a variable part of the stiffness matrix K.

Based on the specified displacements q_{Cj}, the forces R_j can be determined from the relation (2) for u_j equal to q_{Cj}.

As a result of solving the equation (5) one also obtains the displacement vector of bolts q_B:

$$q_B = col(q_{B1}, q_{B2}, \ldots, q_{Bi}, \ldots, q_{Bk}). \tag{7}$$

On the basis of the displacements q_{Bi}, the bolt forces F_{mi} can be computed from the relation:

$$F_{mi} = c_{yi} \cdot q_{Bi} \, . \tag{8}$$

Results and discussion

In order to demonstrate usefulness of the presented method, sample computations of an asymmetrical multi-bolted connection tightened by means of seven M10 bolts were performed.

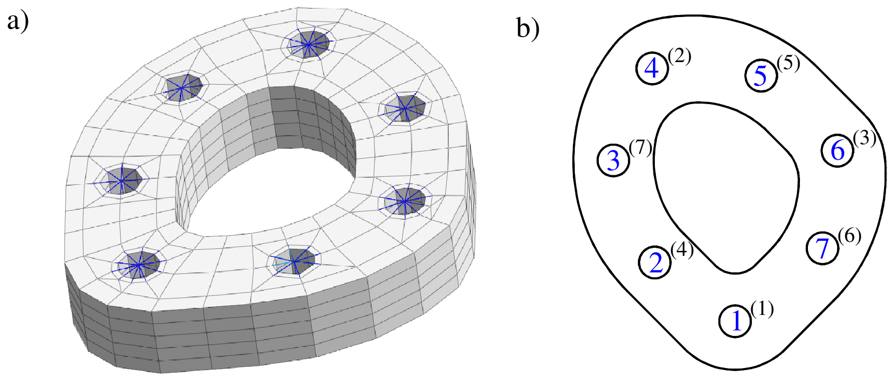

Fig. 3. **Considered multi-bolted connection:** a – simplified FEM-model; b – contact surface

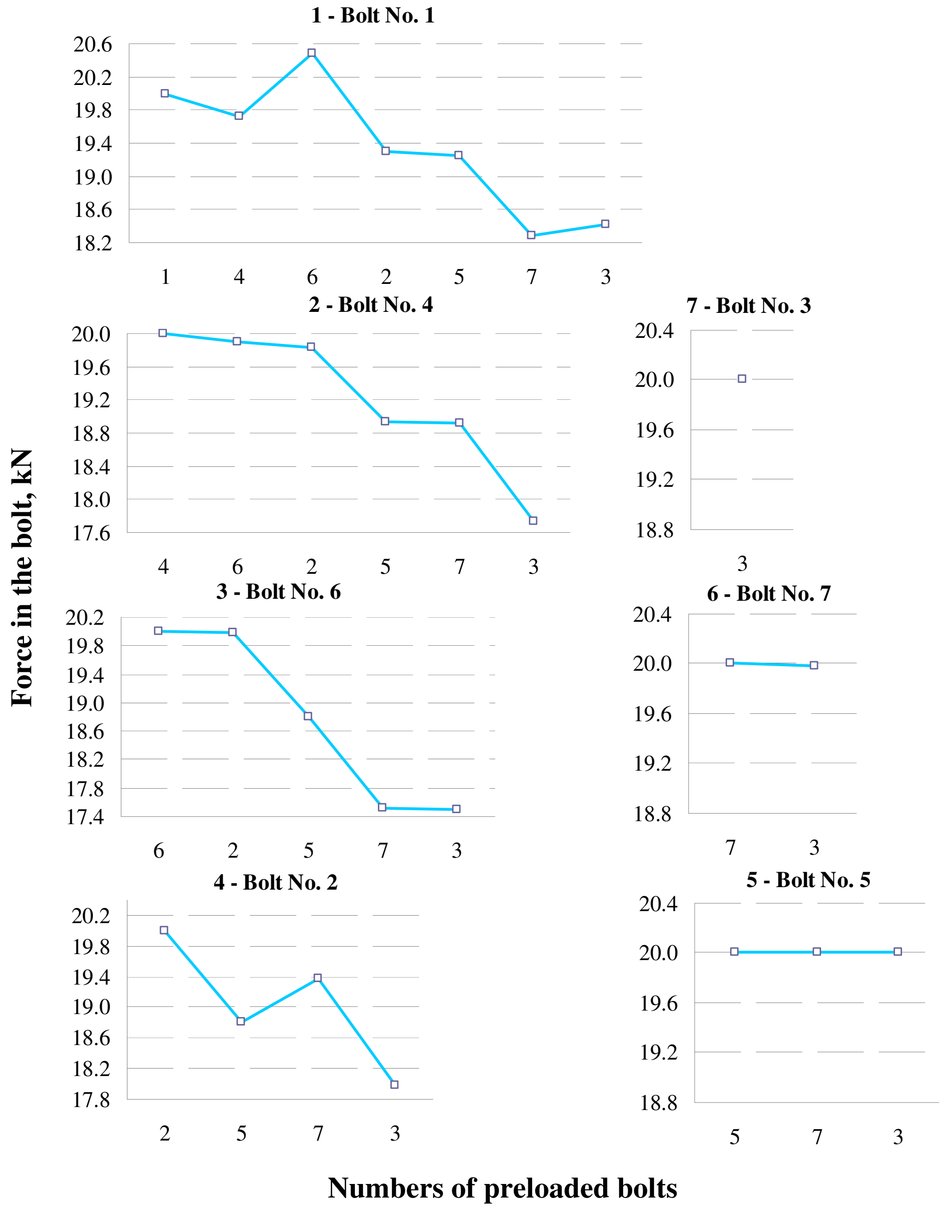

Fig. 4. **Preload values during the assembly process**

A simplified FEM-model of the multi-bolted connection is shown in Figure 3a and a contact surface between the joined elements as well as the bolt arrangement and their numeration are shown in Figure 3b. Calculations were carried out for the joined element thickness *h* equal to 20 mm. The preload of bolts F_{mi} can, for instance, be selected on the basis of the standard [21], in this example it is equal to 20 kN. The tightening sequence taken here is parenthesized in Figure 3b. Characteristics of nonlinear springs are described by the power function [22]:

$$R_j = A_j \cdot (3.428 \cdot u_j^{1.657}). \qquad (9)$$

The results of calculations were put together in graphs presented in Figures 4 and 5. Variations of load in individual bolts during the preloading process are shown in Figure 4 as follows:

- in the first row – force changes in the bolt No. 1 (tensioned as the first bolt);
- in the second row – force changes in the bolts No. 4 and 3 (tensioned as the second and the seventh bolt, respectively);
- in the third row – force changes in the bolts No. 6 and 7 (tensioned as the third and the sixth bolt, respectively);
- in the fourth row – force changes in the bolts No. 2 and 5 (tensioned as the fourth and the fifth bolt, respectively).

Scatter of the final bolt forces at the end of the preloading process is presented in Figure 5.

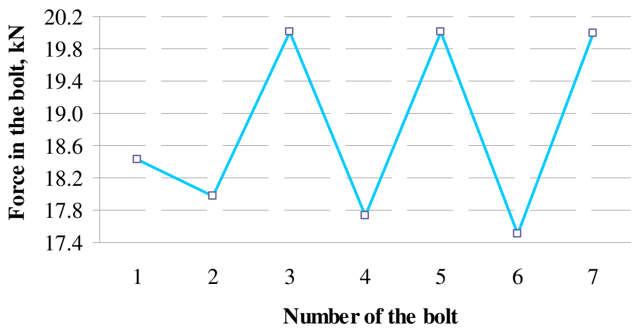

Fig. 5. **Preload values at the end of the assembly process**

Based on the obtained results it can be stated that the preload values of the bolts, both during the assembly process and at the end of this process, are highly variable and irregular. The assessment of the final values of the preload values of the bolts can be conducted on the basis of the *W* index:

$$W = \left| \frac{F_{fin} - F_{mi}}{F_{mi}} \right| \cdot 100\,\%, \qquad (10)$$

where F_{fin} – value of the final preload of the bolt after the assembly process;
F_{mi} – initial value of the preload of the *i*-th bolt at the beginning of the assembly process.

According to the introduced model of the multi-bolted connection the preload values of bolts can be reduced to 12.51 % in relation to their initial values.

Conclusions

Analyses described in the paper lead to the following conclusions:

1. The presented model of the multi-bolted connection can be successfully used in the case of preload variation analysis of joints complying with the adopted model assumptions.
2. The model can also allow to analyze how the tightening sequence affects the preload values in bolts before the preloaded joint is loaded by an operational force.

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