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Modelling Nonlinear Preloaded Multi-Bolted Systems on the Operational State

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Modelling and calculations of asymmetrical multi-bolted connections at the operational stage are presented. The physical model of the joint is based on a flexible flange element that is connected with a flexible support by means of the rigid body 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 analyse the preloaded multi-bolted connections subjected to an eccentric normal load. The results obtained from the sample calculations are presented.

Key words: multi-bolted connection, systemic approach, operational state.

1. Introduction

Multi-bolted connections can be characterised by the following three main features:

- a joint nonlinearity,
- two states of loading and deformation,
- the presence of a structure allowing to treat the joint as a system.

The nonlinearity of multi-bolted connections arises from the fact that they are usually composed of many bodies being in a contact. The source of this nonlinearity are all of contact connections existing between joined elements as well as gaskets often used as additional intermediate elements in this type of connections [1].

Multi-bolted connections before their maintenance are most often preloaded. Thus, in the modelling and calculations of multi-bolted connections both the assembly state (when the joint is mounted) and the operational state (when the preloaded joint is loaded by an external force) should be taken into account.

Papers on modelling and calculations of multi-bolted connections are generally associated with the conventional types of joints such as:

- beam-to-column connections [2–4],
- lap connections [5–7],
- flange connections [8–10].

In all the just mentioned publications, a systemic approach to modelling, calculation and analysing of multi-bolted connections is not taken into account. By contrast, a model of the multi-bolted connection treated as a system consisting of components is presented in this paper, and this system can be considered, modelled and calculated as separate subsystems using the methods adequate to their properties. The aim of this paper is to show the way of modelling such multi-bolted systems with regard to their nonlinearity and the occurrence of the above-mentioned two states of loading and deformation.

The most popular method of modelling and calculations of multi-bolted connections is the finite element method (FEM). Although the joined parts in such connections are usually treated as a spatial body, the bolts are modelled in different ways. In addition to spatial models of the bolts [2, 4, 9, 11], the following main substitute bolt models are used:

- spring models [12, 13],
- rigid body bolt models with the flexible plain part of the bolt and the rigid bolt head [14, 15],
- spider bolt models [16, 17].

In view of the above-mentioned fact, the FEM is also used in this paper for modelling and calculations of the multi-bolted connection, and the rigid body bolt model is chosen as a bolt model.

2. Structure of the multi-bolted system

The structure of the multi-bolted system model results from the concept described in [18]. The model is built with four subsystems shown in Fig. 1:

- **B** – a set of the bolts,
- **F** – the flexible flange element,
- **C** – related to the conventional contact layer,
- **S** – the flexible support.

For such a multi-bolted system, the equation of system equilibrium can be represented as:

$$\mathbf{K} \cdot \mathbf{q} = \mathbf{p}, \tag{2.1}$$

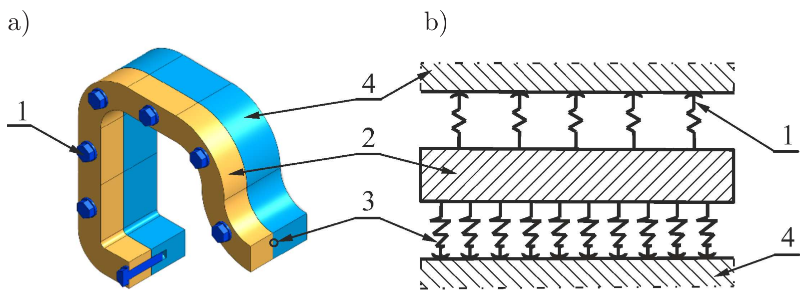

Fig. 1. Multi-bolted system: a) scheme, b) division into subsystems (1 – subsystem **B**, a set of the bolts, 2 – subsystem **F**, the flexible flange element, 3 – subsystem **C**, the conventional contact layer, 4 – subsystem **S**, the flexible support).

where $\mathbf{K}$ is the stiffness matrix, $\mathbf{q}$ is the vector of displacements, and $\mathbf{p}$ is the vector of loads.

After taking into account the division of the system into subsystems, Eq. (2.1) can be expanded to the form:

$$\begin{bmatrix} \mathbf{K}_{BB} & \mathbf{K}_{BF} & \mathbf{0} & \mathbf{K}_{BS} \\ \mathbf{K}_{FB} & \mathbf{K}_{FF} & \mathbf{K}_{FC} & \mathbf{0} \\ \mathbf{0} & \mathbf{K}_{CF} & \mathbf{K}_{CC} & \mathbf{K}_{CS} \\ \mathbf{K}_{SB} & \mathbf{0} & \mathbf{K}_{SC} & \mathbf{K}_{SS} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{q}_B \\ \mathbf{q}_F \\ \mathbf{q}_C \\ \mathbf{q}_S \end{bmatrix} = \begin{bmatrix} \mathbf{p}_B \\ \mathbf{p}_F \\ \mathbf{p}_C \\ \mathbf{p}_S \end{bmatrix}, \tag{2.2}$$

where $\mathbf{K}_{BB}$, $\mathbf{K}_{FF}$, $\mathbf{K}_{CC}$, $\mathbf{K}_{SS}$ are the stiffness matrices of separate subsystems, $\mathbf{K}_{BF}$, $\mathbf{K}_{FB}$, $\mathbf{K}_{BS}$, $\mathbf{K}_{SB}$, $\mathbf{K}_{FC}$, $\mathbf{K}_{CF}$, $\mathbf{K}_{CS}$, $\mathbf{K}_{SC}$ are the matrices of elastic couplings among subsystems, $\mathbf{q}_i$ is the vector of displacements of the i-th subsystem, and $\mathbf{p}_i$ is the vector of loads of the i-th subsystem (i – symbol of the subsystem, $i \in \{B, F, C, S\}$).

With the implemented division of the multi-bolted system, each subsystem can be separately analysed with varying degrees of simplification.

3. Results of calculations

Sample calculations are performed for a selected asymmetrical multi-bolted connection shown in Fig. 2a. The thickness of each of the joined elements is equal to 20 mm. The model of the connection has been fastened in the manner shown in Figs. 2a and 2b by:

- receiving all degrees of freedom on the bottom surface of the lower flange element,

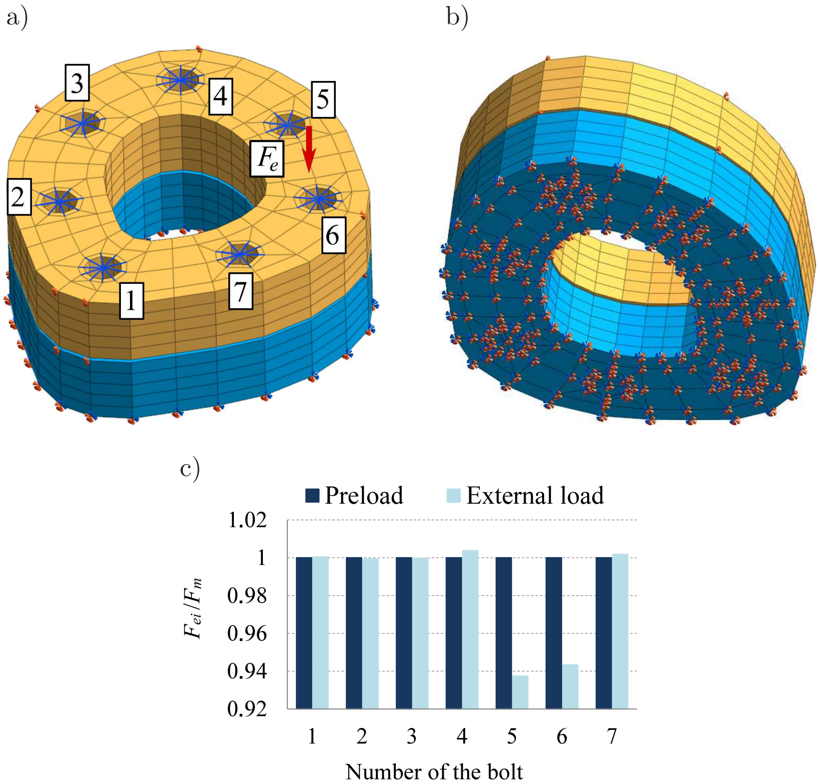

Fig. 2. Example of calculations: a) FEM-based model of the multi-bolted connection, b) fastening of the model, c) bolt force values in the multi-bolted connection loaded externally.

- receiving degrees of freedom in a plane perpendicular to the axis of the bolts in five nodes on the circumference of the upper and lower flange.

The connection is set up by means of seven M10 bolts with the preload F_m equal to 20 kN. In this case, all the bolts are preloaded simultaneously but it is also possible to take into account in the calculations the bolt tensioning conducted according to a specific sequence. The preloaded multi-bolted connection is subjected to the external normal force F_e equal to 30 kN and applied in the manner shown in Fig. 2a.

In the connection, the joined parts are modelled using 3D finite elements and the bolts are replaced by the rigid body bolt models consisting of a flexible plain part of the bolt and a rigid bolt head [18]. Between the flange element and the support the elastic foundation model of Winkler's type is introduced [19]. The contact model is defined using the relationship [17]:

$$R_j = A_j \cdot (3.428 \cdot u_j^{1.657}), \tag{3.1}$$

where R_j is the force in the centre of the j-th elementary contact area (for $j = 1, 2, 3, \ldots, l$), A_j is the j-th elementary contact area, and u_j is the deformation of the j-th nonlinear spring element.

For the modelling and calculations of the multi-bolted system the Midas NFX 2014 program is used [20].

Distribution of operational bolt forces F_{ei} referenced to the preload F_m is illustrated in Fig. 2c. From the results of calculations it can be noticed that the bolts, which are closest to the location of external force applying, are most relieved.

4. Conclusions

The final remarks are as follows:

1. The paper presents a general systemic approach to the modelling and calculations of arbitrary multi-bolted systems. This approach is based on taking into account, in the process of modelling, the real structure of this type of systems, which is composed of: fasteners, joined elements and a contact joint between them.
2. In the sample calculations, the multi-bolted system was loaded with a normal force. However, it is possible to load the system with any force by applying a suitable model of the contact layer between elements joined in the connection.
3. The paper describes the application of the approach in the case of the operational state of the multi-bolted system, but it can also be implemented in the assembly state of the multi-bolted system. At the same time, it can also be used for calculations of typical multi-bolted connections, after the adoption of appropriate assumptions.

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