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Study of the Distribution of Normal Contact Pressure Between Parts Joined in a Multi-Bolted System under Operational Loads

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Modelling and calculations of unsymmetrical multi-bolted connections treated as a system for different bolt models and contact layer models between the joined parts are presented. The modelling refers to preloaded and externally loaded connections. The systemic models of the connection for two substitute models of bolts are shown. Between the joined parts two types of the Winkler model of a contact layer are taken into consideration. Calculations were made for an exemplary unsymmetrical connection. Its models were preloaded and externally loaded with normal forces. As a result of the calculations, distributions of normal contact pressure at the interface of the parts joined in the connection are shown.

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

1. Introduction

In a multi-bolted connection treated as a system [1], it is possible to distinguish, among others, the contact layer at the interface of the joined parts. This contact layer can be replaced with both nonlinear and linear elastic foundation models.

Assuming that the load of the joined parts acts on the direction perpendicular to the surface of their contact, the contact layer can be modelled using the Winkler model [2]. Then contact phenomena between the joined parts can be sufficiently modelled using the normal characteristics of the connection. Such characteristics can be represented with a good approximation by an exponential function [3–5]. However, the contact layer at the interface of the parts joined in the multi-bolted connection is usually operated after its earlier preloading, when the normal characteristics of the connection from nonlinear become close to linear. Therefore, in addition to the application of nonlinear contact characteristics, it is also appropriate in this case to use linearised courses of these characteristics.

Many publications have been made about multi-bolted connections in the operational condition. Most often they refer to multi-bolted connection models created in commercial computer systems based on the finite element method (FEM), and thus built using classic contact models between joined parts available in these systems [6–14]. Huang *et al.* [6] have published a study on several bolted lap connections separated from bridge structures. In their paper they showed variable distribution of forces in the bolts lying in each row of the connections. Saberi *et al.* [7] have compared sensitivity to the bolt diameter on the cyclic behaviour in the case of two different beam-to-column connections. Błachowski and Gutkowski [8] have investigated the impact of damaged circular flange-bolted connections on the behaviour of tall towers using modelling through the multi-level substructuring. Palenica *et al.* [9] have evaluated modal parameters of a building model with structural nodes in the form of multi-bolted connections. Cassiano *et al.* [10] have described results of a parametric analysis on flush end-plate connections under the column removal. The parameters tested by the authors include: a bolt diameter, end-plate thickness, number of bolt rows, type of the beam profile and orientation of the column axis. Tartaglia *et al.* [11] have verified and compared the effectiveness of design procedures of end-plate bolted connections according to American and European standards. Liu *et al.* [12, 13] have studied the influences of a flange thickness, bolt edge distance, flange edge width and bolt hole diameter on the stiffness and strength of rectangular flange connections, bolts tension and contact forces between flanges. Díaz *et al.* [14] have simulated the behaviour of an extended end-plate connection.

All these publications are related to FE-models of steel preloaded and externally loaded connections, however in none of them a systemic approach to modelling of bolted connections is not included. In these models, there is also no possibility of taking into account separate mechanical characteristics for each of the elements in the contact layer between the joined parts.

The subject of modelling steel preloaded multi-bolted systems on the operational state has been initiated in [1], and the current paper is an extension of this subject. The aim of the study is to promote a systemic approach to modelling of multi-bolted connections and to compare the distributions of normal contact pressure at the interface of the joined parts for the following four FE-models of a steel multi-bolted system:

- RBB-NL – a nonlinear system model with the rigid body bolt models (RBB models) [1] and the nonlinear contact layer between the joined parts,

- RBB-L – a linear system model with the rigid body bolt models and the linear contact layer between the joined parts,
- SB-NL – a nonlinear system model with the spider bolt models (SB models) [15] and the nonlinear contact layer between the joined parts,
- SB-L – a linear system model with the spider bolt models and the linear contact layer between the joined parts.

In the multi-bolted system models the Winkler type contact layer between the joined parts is taken into consideration, on the basis of which it is possible to include for each element of the contact layer (for each nonlinear or linear spring, depending on the model) normal mechanical characteristics, for example obtained from experimental tests [16].

2. Structure of the multi-bolted system

The structure of the multi-bolted system is based on the model of four subsystems shown schematically in Fig. 1. These subsystems are:

- subsystem **B** – a set of bolts, replaceable by rigid [1] or flexible [15] models,
- subsystem **F** – the flange,
- subsystem **C** – associated with the contact layer, represented by the nonlinear or linear Winkler model [15],
- subsystem **S** – the support.

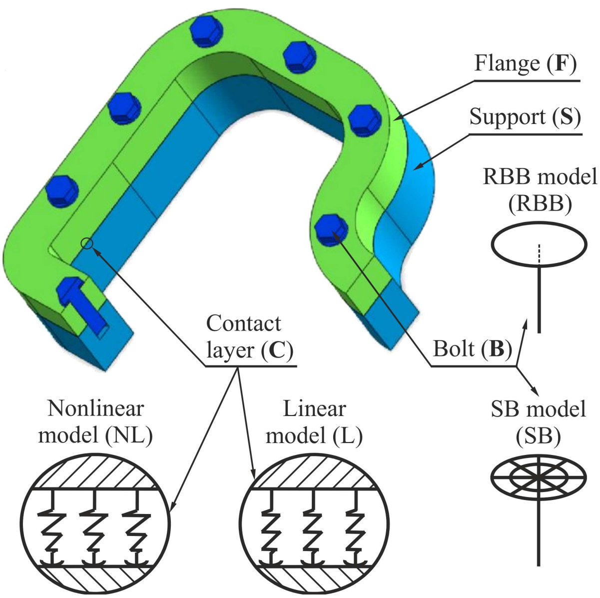

Fig. 1. Scheme of the multi-bolted system and its division into subsystems.

Between the subsystems there are feedback loops, which are shown in Fig. 2. This is also reflected in the block structure of the set of equilibrium equations of the multi-bolted system, which can be written in the following matrix form:

$$\begin{bmatrix} \mathbf{K}_{BB} & \mathbf{K}_{BF} & \mathbf{0} & \mathbf{K}_{BS} \\ \mathbf{K}_{FB} & \mathbf{K}_{FF} & \mathbf{K}_{FC} & \mathbf{0} \\ \mathbf{0} & \mathbf{K}_{CF} & \mathbf{K}_{CC} & \mathbf{K}_{CS} \\ \mathbf{K}_{SB} & \mathbf{0} & \mathbf{K}_{SC} & \mathbf{K}_{SS} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{q}_B \\ \mathbf{q}_F \\ \mathbf{q}_C \\ \mathbf{q}_S \end{bmatrix} = \begin{bmatrix} \mathbf{p}_B \\ \mathbf{p}_F \\ \mathbf{p}_C \\ \mathbf{p}_S \end{bmatrix}, \tag{2.1}$$

where $\mathbf{K}_{BB}$, $\mathbf{K}_{FF}$, $\mathbf{K}_{CC}$, $\mathbf{K}_{SS}$ are the stiffness matrices of the 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 between the subsystems, $\mathbf{q}_i$ is the displacements vector of the i-th subsystem, and $\mathbf{p}_i$ is the loads vector of the i-th subsystem (i is the symbol of the subsystem, $i \in \{B, F, C, S\}$).

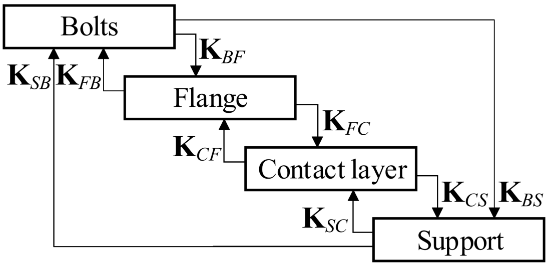

FIG. 2. Feedback loops between the subsystems of the multi-bolted system.

3. Calculations of the multi-bolted system

To demonstrate the usability of the modelling method described above, exemplary calculations of the multi-bolted system shown in Fig. 3a were made. For

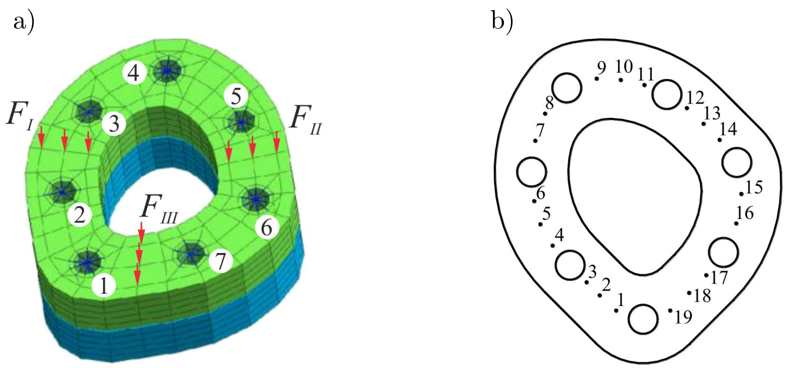

FIG. 3. Model of the system: a) FEM-based model, b) nodes adopted to describe the normal contact pressure distribution ($F_I = F_{II} = F_{III} = 30$ kN).

the modelling and calculations of the system the Midas NFX 2017 R1 program were used. The calculations were carried out for four system models introduced at the beginning of this paper.

The system is asymmetrical to generalize the modelling case. Each of the joined parts (the flange and the support) has a thickness of 20 mm. The connection is tightened by means of seven M10 bolts with the preload F_m equal to 20 kN according to the sequence shown in Table 1 [15].

Table 1. Tightening sequence of the connection.

Number of the preloaded bolt	1	2	3	4	5	6	7
Sequence of the tightening	1	4	6	2	5	7	3

The preloaded multi-bolted system is subjected to an external normal force F_a equal to 30 kN and applied in three places as shown in Fig. 3a (for $a \in \{I, II, III\}$). The location of nodes adopted to describe the normal contact pressure distribution is given in Fig. 3b. The stiffness characteristics of springs forming the contact layer are defined as the following experimental functions [15]:

- for the nonlinear system model

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

- for the linear system model

$$R_j = A_j \cdot (26.873 \cdot u_j), \tag{3.2}$$

where R_j is the force in the centre of the j-th elementary contact area, A_j is the j-th elementary contact area, and u_j is the deformation of the j-th spring element.

The procedure for creating a model of the contact layer from springs with given stiffness characteristics is presented in [17].

Distributions of normal contact pressure at the interface of the parts joined in the multi-bolted system loaded externally by the force F_a is illustrated in Fig. 4.

The assessment of the usefulness of linear models of the multi-bolted system can be carried out based on the W_1 index:

$$W_1 = \frac{p_n^{\text{FEM-L}} - p_n^{\text{FEM-NL}}}{p_n^{\text{FEM-NL}}} \cdot 100, \tag{3.3}$$

where $p_n^{\text{FEM-L}}$ is the value of normal contact pressure on the n-th contact surface, linked to the n-th node, according to the linear multi-bolted system model, and

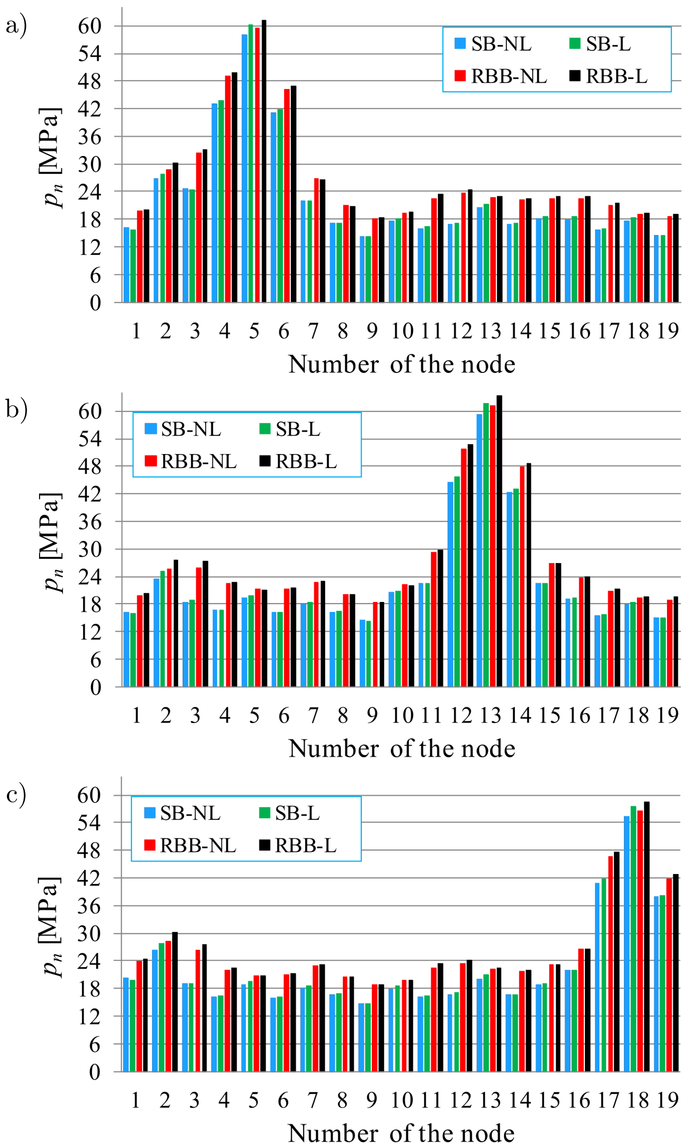

FIG. 4. Distributions of normal contact pressure at the interface of the joined parts for the model loaded by: a) F_I, b) F_{II}, c) F_{III}.

$p_n^{\text{FEM-NL}}$ is the value of normal contact pressure on the n-th contact surface, according to the nonlinear multi-bolted system model (Fig. 3b, $n = 1, 2, ..., 19$).

The maximum values of the W_1 index obtained for all three external load cases of the system are collected in Table 2. Based on the results listed in Table 2 it can be noticed that the use of linear models of the multi-bolted system may cause the overestimation of the normal contact pressure values by 7.6% in the

Table 2. Calculation results for the W_1 index.

Model	External load	W_1 [%]
System with the RBB models	F_I	5.1
	F_{II}	7.6
	F_{III}	6.3
System with the SB models	F_I	4.4
	F_{II}	7.2
	F_{III}	5.5

case of the system with RBB models of the bolts and by 7.2% in the case of the system with SB models of the bolts.

The assessment of the usefulness of adopted bolt models can be carried out based on the W_2 index:

$$W_2 = \frac{p_n^{\mathrm{RBB}} - p_n^{\mathrm{SB}}}{p_n^{\mathrm{SB}}} \cdot 100, \tag{3.4}$$

where p_n^{RBB} is the value of normal contact pressure on the n-th contact surface, according to the multi-bolted system model with RBB models of the bolts, and p_n^{SB} is the value of normal contact pressure on the n-th contact surface, according to the multi-bolted system model with SB models of the bolts.

The maximum values of the W_2 index obtained for all three external load cases of the system are collected in Table 3.

Table 3. Calculation results for the W_2 index.

Model	External load	W_2 [%]
Nonlinear system	F_I	41.0
	F_{II}	40.8
	F_{III}	40.7
Linear system	F_I	42.9
	F_{II}	45.1
	F_{III}	44.0

Based on the results listed in Table 3 it can be noticed that the use of partially rigid bolt models instead of flexible bolt models may cause the overestimation of the normal contact pressure values by about 41% in the case of the nonlinear multi-bolted system model and by about 45% in the case of the linear multi-bolted system model. Further recognition of the suitability of the considered bolt models in the modelling of multi-bolted systems should be continued based on experimental research.

4. Conclusions

Concluding remarks are as follows:

1) In the paper a general systemic approach to modelling and calculations of arbitrary multi-bolted systems is presented. It is possible to apply this approach to systems that are in both operational and assembly state.
2) The proposed multi-bolted system model was loaded with normal forces. However, it is mapped out to add a modified contact layer model to the system to allow the system to be loaded with any force.
3) The modelling approach can be implemented to systems with different bolt models. It is planned to carry out experimental research to determine the usefulness of substitute bolt models in the modelling of multi-bolted systems.

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