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Impact of Nonlinearity of the Contact Layer Between Elements Joined in a Preloaded Bolted Flange Joint on Operational Forces in the Bolts

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Modelling of an asymmetrical preloaded bolted flange joint, loaded with a normal external force is presented. The physical model of the joint is designed as a pair of elements (which are a flexible flange element and a rigid support) clamped using simplified models of bolts. Between the joined elements the Winkler model of a contact layer is introduced. The impact of nonlinearity of the contact layer on operational forces in the bolts is analysed. Conclusions of major importance to modelling of preloaded bolted flange joints are put up.

Keywords: bolted flange joint, FE-modelling, preload, load analysis.

1. Introduction

Bolted flange joints are an important type of structural connections used in mechanical engineering for carrying complex external loads, both static and dynamic. In order to ensure adequate load capacity of these joints they are often designed as preloaded connections [1]. The preload and assertion of a self-locking thread are sufficient for protection against accidental loosening of the bolted flange joint loaded with static forces. By contrast, in the case of the bolted flange joint loaded dynamically, such protection is the use of washers [2]. In each of the above cases bolted flange joints are systems of many elements being in a contact. This in turn generates a number of geometric nonlinearity sources in the joint.

The mechanical characteristics of the contact joint loaded with a normal force are usually nonlinear [3, 4] and can be represented with a good approximation by an exponential function [5, 6]. However, the scope of the nonlinearity of these characteristics depends on the forces acting on the contact joint. In the case of bolted flange joints, in which joined elements are subjected to sequentially tightening by preloaded bolts, the values of these forces are considerable. Then, it can be assumed that the normal characteristic of the contact joint becomes more and more linear with the progress of the tightening process. And at the end of this process, it can already be considered as linear.

Bolted flange joints are most often modelled using the finite element method (FEM). The joined elements are then treated as 3D solid elements or less frequently as 2D planar elements. By contrast, the bolts are modelled by means of:

- a force derived from the preloading [7],
- springs [8, 9],
- beam elements with a rigid head of the bolt [10–12] or with a flexible head of the bolt [13, 14],
- 3D solid elements [15–19].

The use of simplified models of bolts enables to achieve satisfactory calculation results in much shorter time than for complete spatial models.

The aim of this paper is to prove the thesis that modelling of bolted flange joints can be carried out without considering the nonlinearity of a contact layer between the joined elements. Research are executed on the basis of the FEM model of the bolted flange joint with bolts modelled as beam elements with a flexible head of the bolt, and with a linear contact layer between the joined elements. The calculation results are compared with those obtained for the analogical joint model with a nonlinear contact layer between the joined elements, which were presented in [20].

2. Physical model of the bolted flange joint

A model of the bolted flange joint is made of a flexible flange element fastened to a rigid support by means of k bolts with stiffness c_{yi} (for $i = 1, 2, 3, \ldots, k$). The bolts are modelled using the spider bolt models [13, 20] preloaded by the force F_{mi} (Fig. 1).

Between the joined elements the Winkler model of a contact layer is introduced [21], which is built with l springs with the following characteristics [22]:

$$R_j = A_j \, (26.873 \, u_j) \, , \tag{1}$$

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 deformation of the j-th linear spring element (for $j = 1, 2, 3, \ldots, l$).

After the preloading process the system is externally loaded with a normal force F_e. The equation of equilibrium of the system, shown in Fig. 1a, can be written as:

$$\mathbf{K} \cdot \mathbf{q} = \mathbf{p} \tag{2}$$

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

Assuming a systemic approach for modelling of the joint (for a review, see [23]), the equation (2) can be presented in the form:

$$\begin{bmatrix} \mathbf{K}_{BB} & \mathbf{K}_{BF} & \mathbf{0} \\ \mathbf{K}_{FB} & \mathbf{K}_{FF} & \mathbf{K}_{FC} \\ \mathbf{0} & \mathbf{K}_{CF} & \mathbf{K}_{CC} \end{bmatrix} \cdot \begin{bmatrix} \mathbf{q}_B \\ \mathbf{q}_F \\ \mathbf{q}_C \end{bmatrix} = \mathbf{p} \tag{3}$$

where: $\mathbf{K}_{BB}$, $\mathbf{K}_{FF}$, $\mathbf{K}_{CC}$ are the stiffness matrices of separate subsystems, $\mathbf{K}_{BF}$, $\mathbf{K}_{FB}$, $\mathbf{K}_{FC}$, $\mathbf{K}_{CF}$ are the matrices of elastic couplings among subsystems, B represents the subsystem of bolts, F is the flange subsystem, and C represents the contact layer subsystem.

Using the so defined model of the bolted flange joint operational forces and strain in the bolts after the operational state has been completed can be determined.

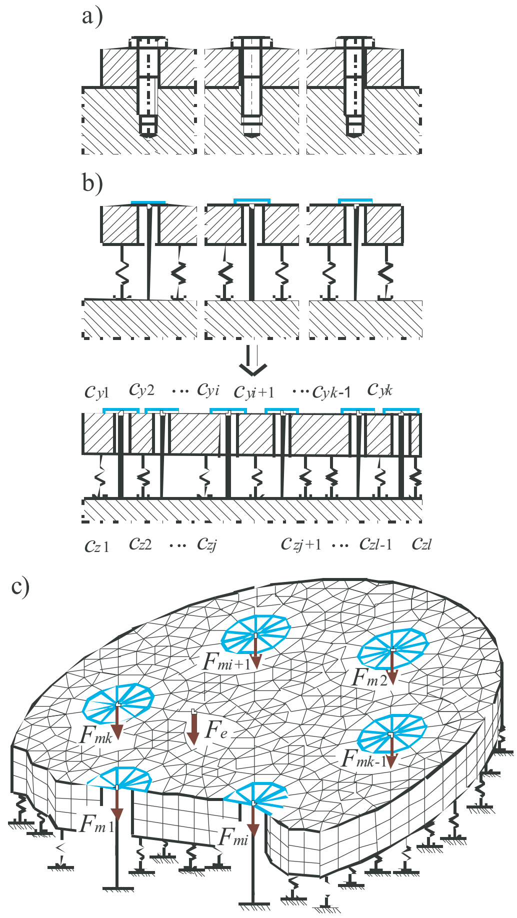

Figure 1 Model of the bolted flange joint: a) scheme, b) elastic properties of the system, c) division into finite elements

As a result of solving the equation (3) one obtains the vector of displacements for the linear springs $\mathbf{q}_C$:

$$\mathbf{q}_C = col\left(q_{C1}, q_{C2}, ..., q_{Cj}, ..., q_{Cl}\right), \tag{4}$$

where: q_{Cj} denotes the displacement of the linear spring No. j.

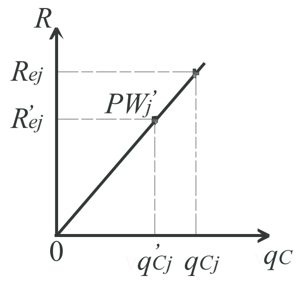

Figure 2 Determining of the working load in the case of elements of the contact layer

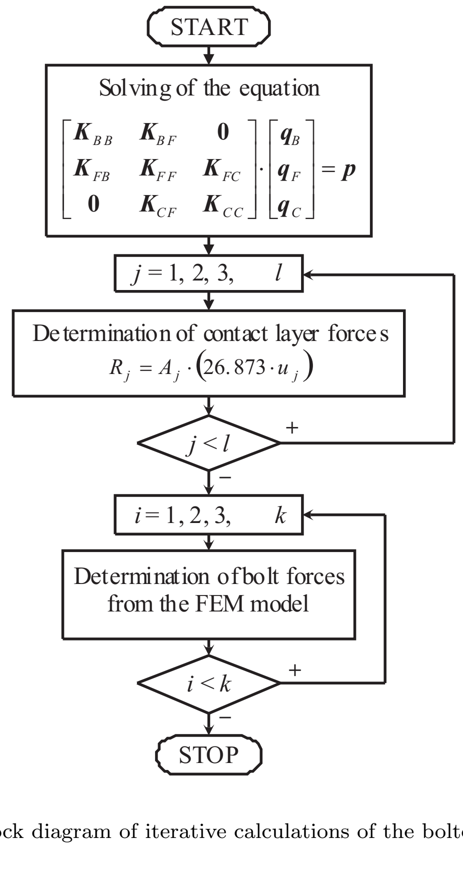

Figure 3 Block diagram of iterative calculations of the bolted flange joint

Final displacements of the linear springs q_{Cj} are measured from the working points $WP_j^{'}$, which determine tension of the springs in the previous step of calculations (Fig. 2). Based on the so defined displacements q_{Cj}, forces in the contact layer R_{ej} can be determined from the relation (1) for u_j equal to q_{Cj}.

The diagram of iterative calculations of the bolted flange joint is shown in Fig. 3.

3. Calculations of the bolted flange joint in the operational condition

To demonstrate the usefulness of the proposed method, sample calculations of the bolted flange joint schematically illustrated in Fig. 4 were performed. The thickness of the flange h is equal to 20 mm.

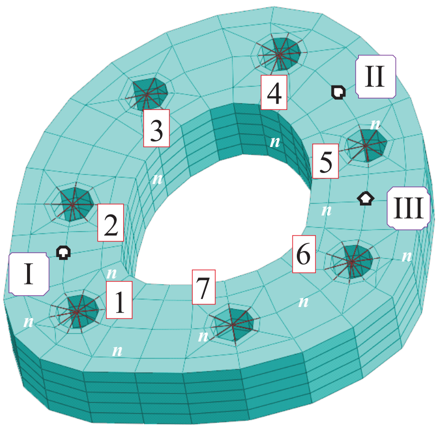

Figure 4 FEM model of the bolted flange joint used for calculations

The joint is preloaded with a force F_m equal to 20 kN sequentially added to seven M10 bolts, and then loaded with an external normal force F_e equal to 50 kN successively applied at points: I, II and III.

The calculation results are compared with the results obtained for an analogical nonlinear model of the joint [20] in Figs. 5–7. On the graphs the following designations are used:

- L – the linear model,
- NL – the nonlinear model.

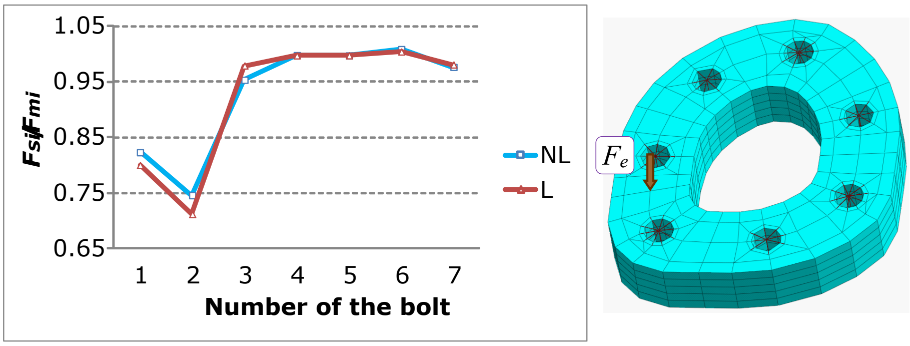

Figure 5 Bolt load values in the joint loaded with the force F_e at the point I

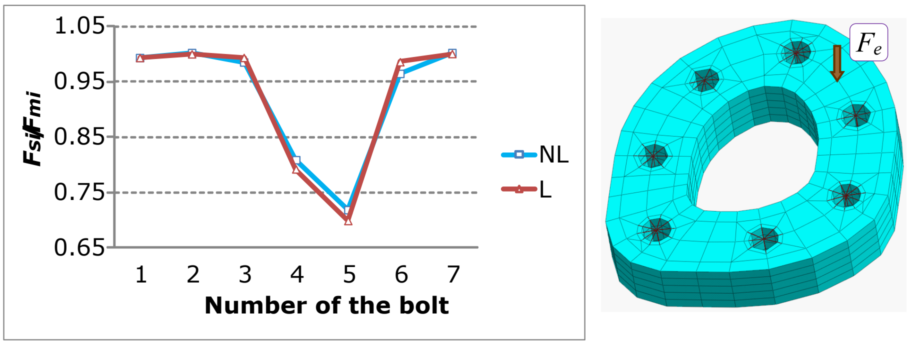

Figure 6 Bolt load values in the joint loaded with the force F_e at the point II

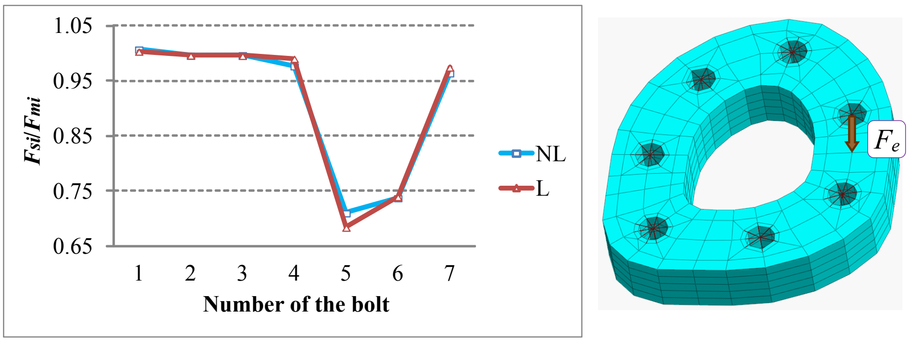

Figure 7 Bolt load values in the joint loaded with the force F_e at the point III

Quantitative comparison of the results can be made on the basis of the W index:

$$W = \left| \frac{F_{si}^{L} - F_{si}^{NL}}{F_{si}^{NL}} \right| 100\ \%, \tag{5}$$

where: F_{si}^{L} is the operational force in the bolt No. i according to the linear model of the joint, and F_{si}^{NL} is the operational force in the bolt No. i according to the nonlinear model of the joint.

Based on the W index values it can be stated that application of the linear model of the joint may lead to obtain operational forces in the bolts with values differing by at most 5 % relative to corresponding forces values achieved for the nonlinear model of the joint.

4. Conclusions

Analysing the results of work the following conclusions are put forward:

1. In the case of the preloaded bolted flange joint, loaded with a normal external force, the nonlinearity of the contact layer between joined elements may have a negligible impact on the values of operational forces in the bolts.

2. The use of a linear model of the contact layer between elements joined in a bolted flange joint provides receiving of calculation results comparable to the results for the corresponding nonlinear model in a significantly shorter time and it is therefore more efficient.

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