Determination of bolt forces and normal contact pressure between elements joined in a multi-bolted system for its assembly condition

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Abstract

Modelling and calculations of asymmetrical nonlinear multi-bolted connections treated as a system composed of four subsystems on the assembly state are presented. These subsystems are: a couple of joined elements (a flange and a support), a contact layer between the elements, and bolts. The physical model of the system is described taking into account the bolt tightening conducted according to a specific sequence. For the modelling the finite element method is used. The flange and the support are built using spatial finite elements. The contact layer is formed as the nonlinear Winkler model, and the bolts are modelled using simplified beam models (named as spider bolt models). The calculation model is presented which can be applied to determine changes in bolt forces as well as in the normal contact pressure between joined elements during the tightening of the system and at its end. Results of sample calculations for the selected multi-bolted system are presented.

Keywords: multi-bolted connection, systemic approach, assembly state

1. Introduction

Multi-bolted connections are frequently applied in mechanical and civil engineering. Most often, they can occur in two states of loading and deformation. The first one is the assembly state in which the connection may be set up under different assembly patterns [1, 11]. Another feature of multi-bolted connections is that contact joints existing between joined parts cause that these connections are usually treated as nonlinear connections. The subject of this paper is modelling of multi-bolted connections regarded as a nonlinear system for the assembly condition.

Papers on modelling and calculations of multi-bolted connections are usually related to the following connections:

- beam-to-column connections [3, 4],
- lap connections [2, 5],
- flange connections [7, 9].

In all the just mentioned publications, a systemic approach to modelling, calculation and analyzing bolted connections is not undertaken.

The most popular method of modelling multi-bolted connections is the finite element method (FEM). While the joined elements in such connections are created mainly as a spatial body, the bolts are modelled in different ways. In addition to the spatial models of bolts [1, 4, 9, 11], the following substitute FE-models of bolts are used:

- spring models [8],
- rigid body bolt models [10],
- spider bolt models [6].

The FEM is also used in this paper for modelling and calculations of the multi-bolted system on the assembly state, and the spider bolt model as a bolt model is chosen.

2. Model of the multi-bolted system

The concept of system approach to modelling multi-bolted connections was presented earlier at the 21st International Conference on Computer Methods in Mechanics [6].

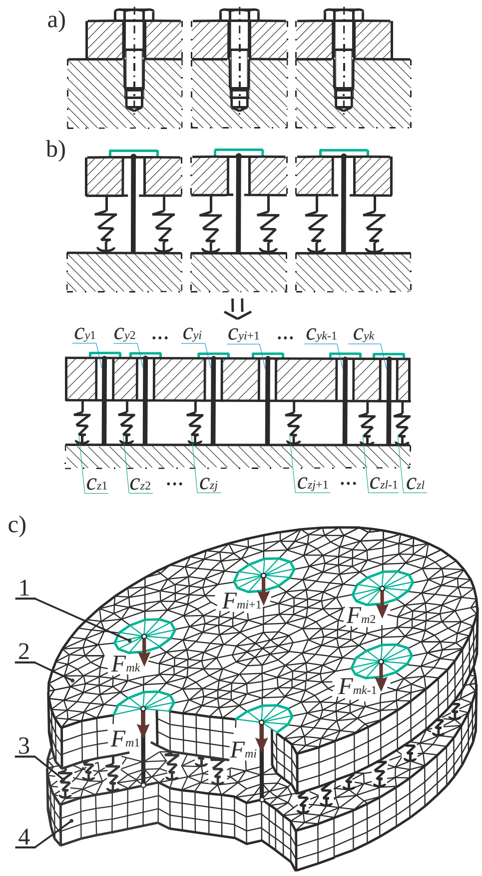


Figure 1: Multi-bolted system: a) scheme, b) description of spring properties, c) FEM-model with spider bolt models (1 – subsystem **B**, the bolts; 2 – subsystem **F**, the flexible flange element; 3 – subsystem **C**, the conventional contact layer; 4 – subsystem **S**, the flexible support)

The model is built from the four subsystems (Fig. 1):
- **B** – the bolts,
- **F** – the flexible flange element,
- **C** – the conventional contact layer,
- **S** – the flexible support.

After taking into consideration the division of the multi-bolted system into subsystems, the equation of system equilibrium can be presented in the form

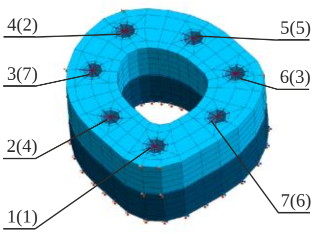
$$\begin{bmatrix} \boldsymbol{K}_{BB} & \boldsymbol{K}_{BF} & \boldsymbol{0} & \boldsymbol{K}_{BS} \\ \boldsymbol{K}_{FB} & \boldsymbol{K}_{FF} & \boldsymbol{K}_{FC} & \boldsymbol{0} \\ \boldsymbol{0} & \boldsymbol{K}_{CF} & \boldsymbol{K}_{CC} & \boldsymbol{K}_{CS} \\ \boldsymbol{K}_{SB} & \boldsymbol{0} & \boldsymbol{K}_{SC} & \boldsymbol{K}_{SS} \end{bmatrix} \cdot \begin{bmatrix} \boldsymbol{q}_B \\ \boldsymbol{q}_F \\ \boldsymbol{q}_C \\ \boldsymbol{q}_S \end{bmatrix} = \begin{bmatrix} \boldsymbol{p}_B \\ \boldsymbol{p}_F \\ \boldsymbol{p}_C \\ \boldsymbol{p}_S \end{bmatrix} \tag{1}$$

where $\boldsymbol{K}_{aa}$ is the stiffness matrix of the a-th subsystem, $\boldsymbol{K}_{ab}$ is the matrix of elastic couplings between the a-th and b-th subsystems, $\boldsymbol{q}_a$ is the vector of displacements of the a-th subsystem, and $\boldsymbol{p}_a$ is the vector of loads of the a-th subsystem (a, b – symbols of the subsystems, $a \in \{B, F, C, S\}$, $b \in \{B, F, C, S\}$).

3. Calculations of the multi-bolted system on the assembly state

Sample calculations were performed for a selected asymmetrical multi-bolted system shown in Fig. 2.

a)



b)

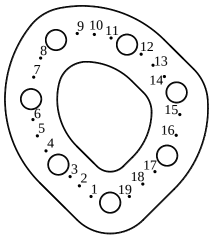


Figure 2: Analyzed multi-bolted system: a) FEM-based model with the numbering of the bolts and the tightening sequence given in parentheses, b) nodes on the contact surface of the joined elements adopted to describe normal contact pressure distribution

The model was built using the Midas NFX 2017 program. The connection is fastened using seven M10 bolts. Calculations were made for the joined elements with a thickness of 20 mm and the preload of bolts equal to 20 kN. The tightening sequence is given in parentheses in Fig. 2.

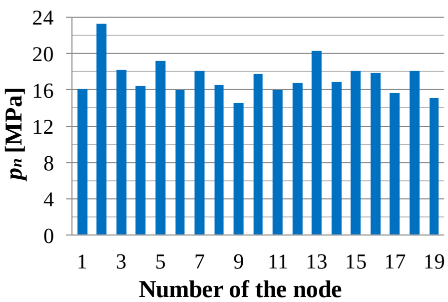


Figure 3: Diagram of normal contact pressure between joined elements at the end of the assembly state

As a result of the calculations, the bolt forces distributions and distributions of normal contact pressure on elementary surfaces located on the line joining the nodes defined in Fig. 2b, during the tightening process and at the end of this process, are obtained. Sample calculation results are show in Fig. 3.

4. Conclusions

The described model of the multi-bolted system can be successfully used in analysis of preload variations and normal contact pressure between joined elements variations in the case of any connection of flexible elements. The model can also provide analysis of how the tightening sequence affects the preload values in bolts before the preloaded system is loaded by an external force.

References

[1] Abid, M., Khan, A., Nash, D.H., Hussain, M. and Wajid, H.A., Simulation of optimized bolt tightening strategies for gasketed flanged pipe joints, *Procedia Engineer.*, 130, pp. 204-213, 2015.

[2] Ascione, F., A preliminary numerical and experimental investigation on the shear stress distribution on multi-row bolted FRP joints, *Mech. Res. Commun.*, 37, pp. 164-168, 2010.

[3] Brunesi, E., Nascimbene, R. and Rassati, G.A., Seismic response of MRFs with partially-restrained bolted beam-to-column connections through FE analyses, *J. Constr. Steel Res.*, 107, pp. 37-49, 2015.

[4] Chen, X. and Shi, G., Finite element analysis and moment resistance of ultra-large capacity end-plate joints, *J. Constr. Steel Res.*, 126, pp. 153-162, 2016.

[5] Chowdhury, N.M., Chiu, W.K., Wang, J. and Chang, P., Experimental and finite element studies of bolted, bonded and hybrid step lap joints of thick carbon fibre/epoxy panels used in aircraft structures, *Compos. Part B-Eng.*, 100, pp. 68-77, 2016.

[6] Grzejda, R., New method of modelling nonlinear multi-bolted systems, *Advances in Mechanics: Theoretical, Computational and Interdisciplinary Issues*, CRC Press/Balkema, Leiden, pp. 213-216, 2016.

[7] Jakubowski, A. and Schmidt, H., Numerical investigations on the fatigue-relevant bolt stresses in preloaded ring flange connections with imperfections (in German), *Stahlbau*, 73, pp. 517-524, 2004.

[8] Luan, Y., Guan, Z.-Q., Cheng, G.-D. and Liu, S., A simplified nonlinear dynamic model for the analysis of pipe structures with bolted flange joints, *J. Sound Vib.*, 331(2), pp. 325-344, 2012.

[9] Mourya, R.K., Banerjee, A. and Sreedhar, B.K., Effect of creep on the failure probability of bolted flange joints, *Eng. Fail. Anal.*, 50, pp. 71-87, 2015.

[10] Palenica, P., Powałka, B. and Grzejda, R., Assessment of modal parameters of a building structure model, *Springer Proceedings in Mathematics & Statistics*, 181, pp. 319-325, 2016.

[11] Zhang, L.Z., Liu, Y., Sun, J.C., Ma, K., Cai, R.L. and Guan, K.S., Research on the assembly pattern of MMC bolted flange joint, *Procedia Engineer.*, 130, pp. 193-203, 2015.