MODELLING NONLINEAR MULTI-BOLTED CONNECTIONS: A CASE OF OPERATIONAL CONDITION

Rafal Grzejda
West Pomeranian University of Technology, Szczecin, Poland
rafal.grzejda@zut.edu.pl

Abstract. The report deals with modelling and calculations of asymmetrical multi-bolted connections at the operational 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 any preloaded multi-bolted connection subjected to an eccentric normal load. The sample results obtained from the calculations are presented.

Keywords: multi-bolted connection, FE-modelling, bolt force.

Introduction

Preloaded multi-bolted connections are usually designed for carrying very differential external loads. Among them, there are asymmetrical joints with an arbitrary arrangement of bolts commonly applied in mechanical engineering (also for applications in agriculture engineering). Multi-bolted connections are systems of many bodies being in a contact [1-3]. Such connections very often should be treated as nonlinear systems. This nonlinearity is caused by both contact phenomena between joined elements [4-6] and stiffness characteristics of washers or gaskets occurring in these joints [7-9]. Meanwhile, there is no possibility to take into account the real stiffness characteristics for the contact joints. Instead of this, standard models of the contact joint appropriate for the adopted method of modelling are used [10; 11]. Generally, papers on modelling and calculations of multi-bolted connections mostly deal with typical joints, which are geometrically symmetrical or symmetrically loaded, such as:

- bolted angle connections [12; 13];
- bolted end-plate connections [14; 15];
- bolted flange connections [6; 9].

Additionally, the assembly state of multi-bolted connections that takes place before external loading is sometimes omitted [16]. The comprehensive solution of all the problems appearing in multi-bolted connections, especially in the case of asymmetrical joints, has not yet been carried out, so the task of modelling multi-bolted connections is still valid and important.

The most popular method of modelling and calculations of multi-bolted connections is the finite element method (FEM) [17]. Although the elements joined in such connections are typically modeled as a spatial body, the bolts are modeled in different ways. They can be treated, inter alia, as:

- applied preload (in this case there are no bolt models) [18];
- linear springs [19];
- hybrid elements consisting of the flexible plain part of the bolt and the rigid bolt head [20; 21];
- spider bolt models [18; 22];
- 3D elements [2; 5; 23].

In the previous paper [20] some results of theoretical investigations of an asymmetrical preloaded multi-bolted connection, composed of a flange element fastened to a rigid support and subjected to an external normal load, were released. The theme of the paper is treating the multi-bolted connection as a system composed of subsystems. This approach enables modelling of each subsystem separately using different models to find the best one of them. In the previous model of the joint [20] bolts were treated as rigid body bolt elements consisted of a flexible plain part of the bolt and a rigid bolt head. In the current paper some new results of modelling multi-bolted connections are presented. In the new model, bolts are treated as spider bolt elements [22]. For modelling and calculations of the multi-bolted connection the finite element method is used.

In this paper the second stage of modelling and calculations of multi-bolted connections is presented, which is related to the case of the operational condition. The earlier stage, which is associated with the case of the assembly condition, is shown in [16].

Materials and methods

A general structure of the multi-bolted connection model results from an idea presented in the article [20]. 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 [22], which substitute bolts. Spring properties of the i-th model of the bolt (for $i = 1, 2, \dots, k$) are determined from the relation [20]:

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

where c_{yi} – stiffness coefficient of the bolt, $N \cdot mm^{-1}$;
c_n – stiffness coefficient of the n-th bolt's fragment, $N \cdot mm^{-1}$.

Between the joined elements the nonlinear contact model is 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 relationship [20]:

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

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

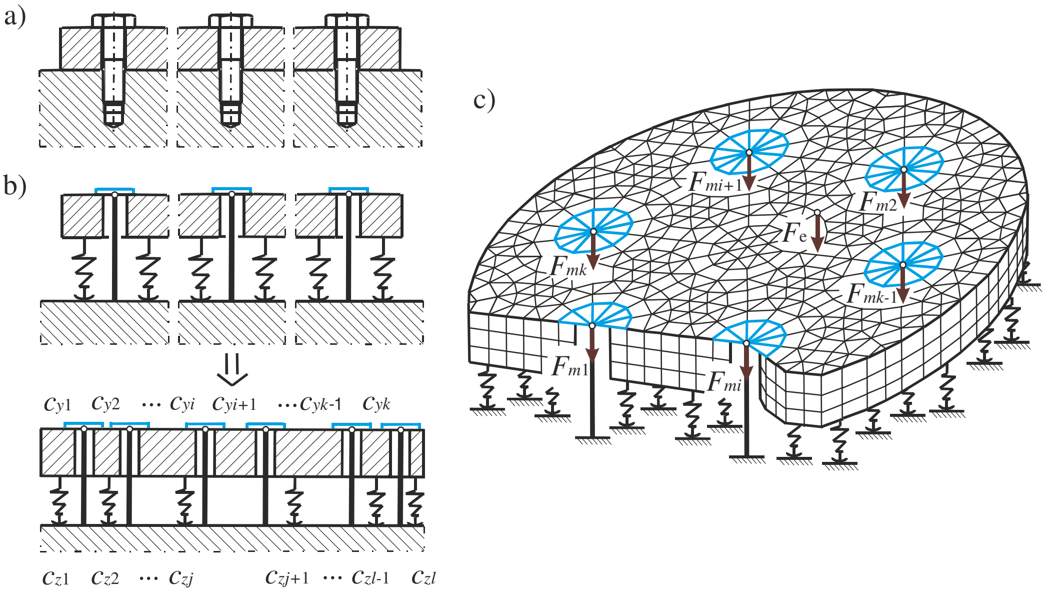

Fig. 1. **Multi-bolted connection:** a) scheme; b) description of spring properties; c) preloaded FEM-model with spider bolt models loaded externally by the normal force F_e

The equation of system equilibrium of the multi-bolted connection can be written in the form:

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

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

Assuming the division of the system into three subsystems, according to the nomenclature adopted in [16], by which B is the subsystem composed of the bolts, F is the flexible flange element and C is the subsystem associated with the conventional contact layer, the equation (3) can be represented as:

$$\begin{bmatrix} K_{BB} & K_{BF} & 0 \\ K_{FB} & K_{FF} & K_{FC} \\ 0 & K_{CF} & K_{CC} \end{bmatrix} \cdot \begin{bmatrix} q_B \\ q_F \\ q_C \end{bmatrix} = p \,, \quad (4)$$

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, both displacements of bolts and bolt forces during the operational state can be evaluated.

Calculations of the multi-bolted connection are accomplished in an iterative process. At the very beginning of this process, in the equation (4) the stiffness matrix of the bolt subsystem K_{BB} and the stiffness matrix of the contact layer subsystem K_{CC} received at the end of the assembly process [16] are taken into account. As a result of solving the equation (4) one obtains the displacement vector of nonlinear springs q_C [20]:

$$q_C = col\left(q_{C1}, q_{C2}, \ldots, q_{Cj}, \ldots, q_{Cl}\right). \quad (5)$$

With the use of 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 (4) one obtains the displacement vector of bolts $\boldsymbol{q}_B$ too [20]:

$$q_B = col\left(q_{B1}, q_{B2}, \ldots, q_{Bi}, \ldots, q_{Bk}\right). \quad (6)$$

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

$$F_{si} = c_{yi} \cdot q_{Bi} \,. \quad (7)$$

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 and then loaded externally were performed.

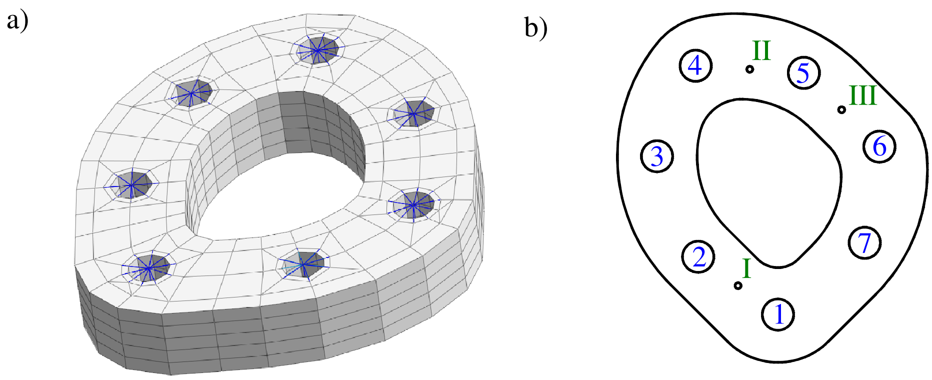

Fig. 2. **Considered multi-bolted connection:** a – simplified FEM-model; b – contact surface with the adopted numbering of bolts and location of an external normal force

A simplified FEM-model of the considered multi-bolted connection is shown in Figure 2a and a contact surface between joined elements as well as the bolt arrangement and their numeration are shown in Figure 2b. Adopted here connections were tested experimentally on a laboratory stand to verify the way of modelling [24]. Calculations were carried out for the joined element's thickness $h = 20$ mm. The preload of bolts F_{mi} is equal to 20 kN. Characteristics of nonlinear springs are represented by the following function [25]:

$$R_j = A_j \cdot (3{,}428 \cdot u_j^{1{,}657})\,. \qquad (8)$$

After the preloading process, the multi-bolted connection is subjected to an eccentric normal force F_e equal to 50 kN acting consecutively at three points (I, II, III), shown in Figure 2b.

Results of calculations were put together in graphs illustrated in Figures 3-5 according as three points of the force F_e acting. In the respective figures, the values of bolt forces F_{si} related to preloads F_{mi} [16] are presented.

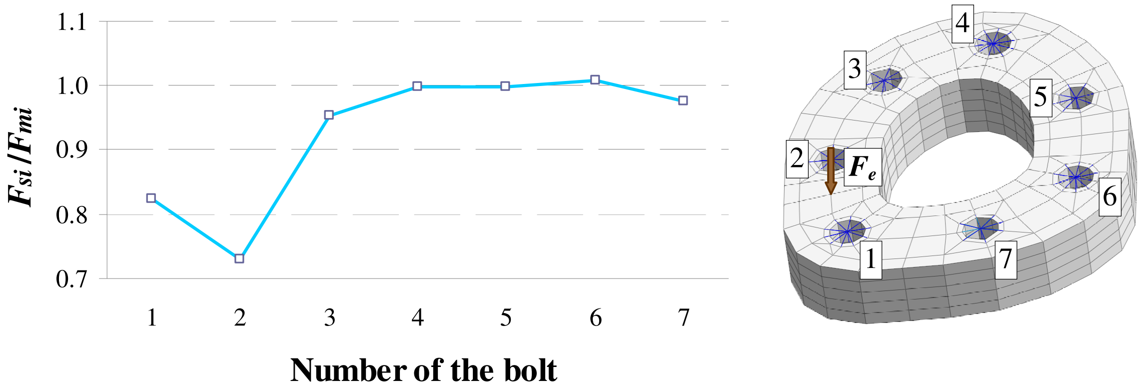

Fig. 3. **Bolt load values in the joint loaded by an external force at the point I**

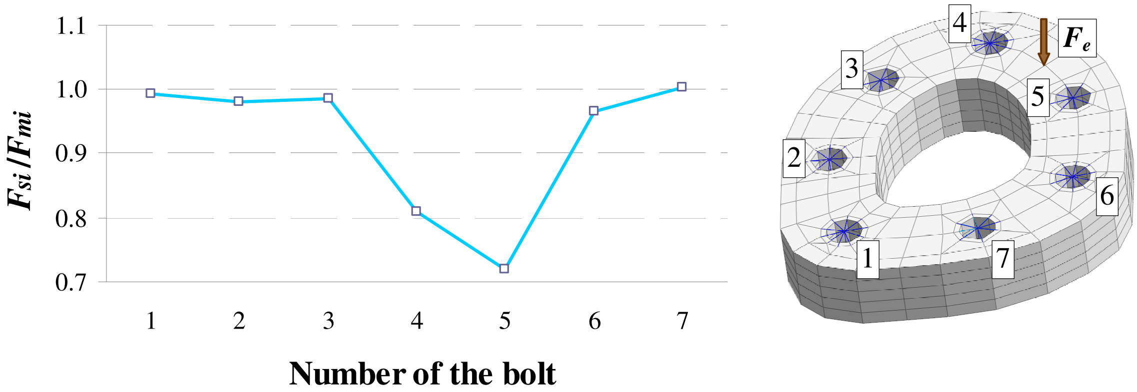

Fig. 4. **Bolt load values in the joint loaded by an external force at the point II**

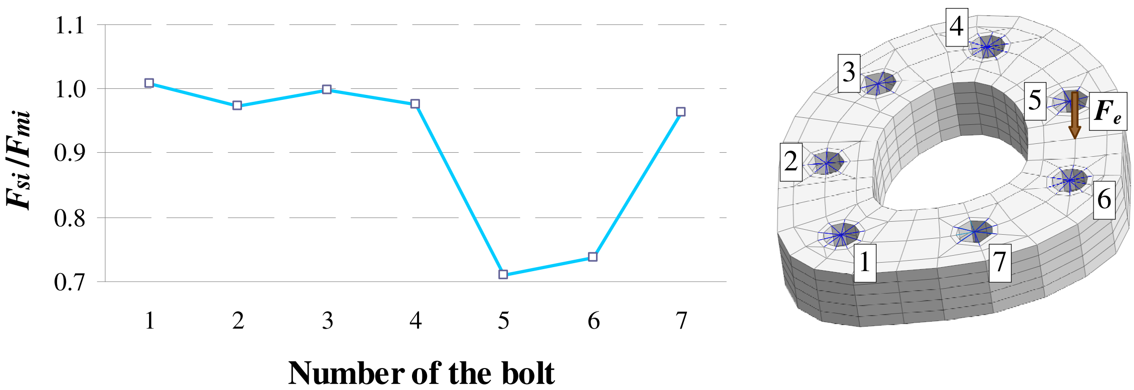

Fig. 5. **Bolt load values in the joint loaded by an external force at the point III**

Based on the obtained diagrams, it can be noted that the largest decrease in the bolt forces after applying the external force to the multi-bolted connection occurs in the bolts lying nearest to the point of application of the force F_e. In the next bolts (the bolts No. 3 and 7 in Figure 3, as well as the bolts No. 3 and 6 in Figure 4 and the bolts with No. 4 and 7 in Figure 5) there is a partial reduction of the bolt forces in relation to their preload. The forces in the bolts most distant from the point of application of the external force almost do not change in comparison with their preload.

Analyzing all cases, the largest bolt force for the proposed method of external loading the multi-bolted connection only slightly exceeds the value of the adopted preload. Assuming this result as most exacting and taking into account the provisions in the standard [26], in the considered connection the bolts in the class of mechanical properties from the set {9.8, 10.9, 12.9} should be selected. On the other hand, accepting that the bolts in this connection can even be loaded by the ultimate tensile load [26], then the bolts in the class of mechanical properties from the set {4.6, 4.8, 5.6, 5.8, 6.8, 8.8, 9.8, 10.9, 12.9} could be chosen.

Conclusions

Analyses described in the paper lead to the following conclusions:

1. The presented model of the preloaded multi-bolted connection subjected to an external normal load can be successfully used in the case of bolt forces variation analysis of joints complying with the adopted model assumptions.
2. The model can be modified to carry out analysis of the multi-bolted connection loaded by an arbitrary external force by applying an appropriate contact model including also the tangential stiffness.

References

1. Abid M., Khan A., Nash D.H., Hussain M., Wajid H.A. Simulation of optimized bolt tightening strategies for gasketed flanged pipe joints. Procedia Engineering, vol. 130, 2015, pp. 204-213.
2. Błachowski B., Gutkowski W. Effect of damaged circular flange-bolted connections on behaviour of tall towers, modelled by multilevel substructuring. Engineering Structures, vol. 111, 2016, pp. 93-103.
3. Taheri-Behrooz F., Shamaei Kashani A.R., Hefzabad R.N. Effects of material nonlinearity on load distribution in multi-bolt composite joints. Composite Structures, vol. 125, 2015, pp. 195-201.
4. Augusto H., da Silva L.S., Rebelo C., Castro J.M. Characterization of web panel components in double-extended bolted end-plate steel joints. Journal of Constructional Steel Research, vol. 116, 2016, pp. 271-293.
5. Kalogeropoulos A., Drosopoulos G.A., Stavroulakis G.E. Thermal-stress analysis of a three-dimensional end-plate steel joint. Construction and Building Materials, vol. 29, 2012, pp. 619-626.
6. Mayer M.H., Gaul L. Segment-to-segment contact elements for modelling joint interfaces in finite element analysis. Mechanical Systems and Signal Processing, vol. 21, No. 2, 2007, pp. 724-734.
7. Chen Y., Xu Y.Y., Huang L.Y., Xu Y.H., Guan K.S. Creep behavior of metal-to-metal contact bolted flanged joint. Procedia Engineering, vol. 130, 2015, pp. 214-220.
8. Murali Krishna M., Shunmugam M.S., Siva Prasad N. A study on the sealing performance of bolted flange joints with gaskets using finite element analysis. International Journal of Pressure Vessels and Piping, vol. 84, No. 6, 2007, pp. 349-357.
9. Roos E., Kockelmann H., Hahn R. Gasket characteristics for the design of bolted flange connections of metal-to-metal contact type. International Journal of Pressure Vessels and Piping, vol. 79, No. 1, 2002, pp. 45-52.
10. Baran E., Akis T., Sen G., Draisawi A. Experimental and numerical analysis of bolted connection in steel transmission towers. Journal of Constructional Steel Research, vol. 121, 2016, pp. 253-260.
11. Thai H.-T., Uy B. Finite element modelling of blind bolted composite joints. Journal of Constructional Steel Research, vol. 112, 2015, pp. 339-353.
12. Pirmoz A., Seyed Khoei A., Mohammadrezapour E., Saedi Daryan A. Moment-rotation behavior of bolted top-seat angle connections. Journal of Constructional Steel Research, vol. 65, No. 4, 2009, pp. 973-984.
13. Saedi Daryan A., Ziaei M., Amirodin Sadrnejad S. The behavior of top and seat bolted angle connections under blast loading. Journal of Constructional Steel Research, vol. 67, No. 10, 2011, pp. 1463-1474.
14. Girão Coelho A.M. Rotation capacity of partial strength steel joints with three-dimensional finite element approach. Computers and Structures, vol. 116, 2013, pp. 88-97.

15. Shi G., Shi Y., Wang Y., Bradford M.A. Numerical simulation of steel pretensioned bolted end-plate connections of different types and details. Engineering Structures, vol. 30, No. 10, 2008, pp. 2677-2686.
16. Grzejda R. Modelling nonlinear multi-bolted connections: A case of the assembly condition. Proceedings of 15th International Scientific Conference “Engineering for Rural Development 2016“, May 25-27, 2016, Jelgava, Latvia, pp. 329-335.
17. Adams V., Askenazi A. Building better products with Finite Element Analysis. Santa Fe: OnWord Press, 1999.
18. Kim J., Yoon J.-Ch., Kang B.-S. Finite element analysis and modeling of structure with bolted joints. Applied Mathematical Modelling, vol. 31, No. 5, 2007, pp. 895-911.
19. Luan Y. Guan Z.-Q., Cheng G.-D., Liu S. A simplified nonlinear dynamic model for the analysis of pipe structures with bolted flange joints. Journal of Sound and Vibration, vol. 331, No. 2, 2012, pp. 325-344.
20. Grzejda R. Determination of bolt forces for the operational state of a bolted flange connection. Advances in Manufacturing Science and Technology, vol. 37, No. 3, 2013, pp. 73-83.
21. Hammami C., Balmes E., Guskov M. Numerical design and test on an assembled structure of a bolted joint with viscoelastic damping. Mechanical Systems and Signal Processing, vol. 70-71, 2016, pp. 714-724.
22. Grzejda R. New method of modelling nonlinear multi-bolted systems. Advances in Mechanics: Theoretical, Computational and Interdisciplinary Issues, Proceedings of the 3rd Polish Congress of Mechanics (PCM) and 21st International Conference on Computer Methods in Mechanics (CMM), September 8-11, 2015, Gdansk, Poland, Leiden: CRC Press, 2016, pp. 213-216.
23. Zhang L.Z., Liu Y., Sun J.C., Ma K., Cai R.L., Guan K.S. Research on the assembly pattern of MMC bolted flange joint. Procedia Engineering, vol. 130, 2015, pp. 193-203.
24. Grzejda R., Witek A., Konowalski K. Doświadczalne badania niesymetrycznego połączenia wielośrubowego obciążonego mimośrodowo (Experimental investigations of an asymmetrical bolted connection loaded by an eccentric force). Przegląd Mechaniczny, vol. 71, No. 1, 2012, pp. 21-27 (in Polish).
25. Grzejda R. Designation of a normal stiffness characteristic for a contact joint between elements fastened in a multi-bolted connection. Diagnostyka, vol. 15, No. 2, 2014, pp. 61-64.
26. PN-EN ISO 898-1:2013-06 (E) standard “Mechanical properties of fasteners made of carbon steel and alloy steel. 1. Part: Bolts, screws and studs with specified property classes – Coarse thread and fine pitch thread”.