R.Grzejda[1], K.Kwiatkowski[2], A.Parus[3]

EXPERIMENTAL AND NUMERICAL INVESTIGATIONS OF AN ASYMMETRIC MULTI-BOLTED CONNECTION PRELOADED AND SUBJECTED TO MONOTONIC LOADS

West Pomeranian University of Technology in Szczecin, Faculty of Mechanical Engineering and Mechatronics, Al. Piastów 19, 70-310 Szczecin, Poland;
[1]email: rafal.grzejda@zut.edu.pl; [2]konrad.kwiatkowski@zut.edu.pl;
[3]arkadiusz.parus@zut.edu.pl

Abstract. The experimental tests of a seven-bolted connection with an asymmetric contact area between the joined elements are presented. The research is divided into two stages. In the first one, the connection is preloaded in a three-pass cycle. In the second stage, the connection is loaded with a monotonic alternating force applied at an angle of 30 degrees to the contact surface of the joined elements to generate compressive and shear forces in the connection. The tests are carried out with the use of the INSTRON 8850 testing machine. As a result, the courses of forces in the bolts measured with the use of resistance strain gauges and the relative displacements between the joined elements measured with an extensometer are shown. In the second part, the modeling of the connection in the convention of the finite element method is presented. The joined elements are modeled with the use of spatial finite elements, and the fasteners – as the hybrid elements made of deformable beams, rigid heads, and rigid nuts. The paper is completed with a comparison of the results obtained from the measurements and calculations, based on which the conclusions important from the point of view of the FEM analysis are drawn.

Key words: multi-bolted connection, preload, monotonic loading, finite element method.

1. Introduction.

Bolt and multi-bolted connections are common joints in many structures that must be reliable [27]. For this reason, researchers are still looking for models of bolted connections that would best reflect their behavior under operating conditions [15] or would allow to predict the reliability of bolted structures under these conditions [16].

A well-known practice to verify the accuracy of the numerical modelling method is to compare its results with the results of experimental studies. This is especially important in the case of modelling connections of several elements with contact joints [8]. An example of such connections are multi-bolted connections, the research and modelling of which are the subject of this paper.

Apart from a few exceptions [28, 29], experimental investigations of multi-bolted connections under external static loads have so far been carried out mainly for connections characterised by geometric symmetry. A review of papers on experimental studies and modelling of multi-bolted connections is presented below with reference to the classic types of these connections, i.e. flange, lap and column connections.

Jaszak [15] has showed that the use of an elastic serrated gasket improves the tightness class of the bolted flange connection by the order of magnitude. The compressive and bending shear strength of bolted flange connections has been investigated by Liu et al. [21] and the tensile strength of bolted flange connections has been tested by Couchaux et al. [2].

Kim et al. [18] have performed research for single-shear four-bolted connections in order to investigate the structural behavior of the connections, such as ultimate strength and fracture mode. Similar studies, but for double-shear connections, have been presented by Kiyokawa et al. [19]. The research on the stiffness of the selected bolted lap connection has been discussed by Puchała et al. [26]. A comprehensive review on the fatigue strength analysis of shear bolted connections have been carried out in [30].

Kawecki and Kozlowski [17] have conducted investigation of four extended end-plate welded girder splices with multiple bolt rows, and multiple bolts per row. Gordziej-Zagórowska et al. [7] have determined the deformation forms and strains in the case of bolted connections with positive eccentricity in truss system, and Boudia et al. [1] have tested the deformation forms in the case of beam-to-column bolted connections with various stiffeners. A comprehensive review on the modelling of the beam-to-column connection behavior in steel frames have been carried out in [3].

The above-mentioned papers can be divided into two groups, depending on the numerical methods adopted in them. The first group includes papers based on Eurocode 3 [25] and concerns papers [7, 17, 28]. The second group consists of papers based on the finite element method (FEM) [1, 2, 18, 19, 21, 26, 29]. Based on the available literature, it can be concluded that the finite element method is currently the most popular method of modelling multi-bolted connections and other mechanical systems [4]. Therefore, this method was also used in our paper. The modelling was performed in the Midas NFX 2020 R2 finite element system.

Even though the papers cited above expressed in-depth research, there are still many areas in which knowledge of the behavior of any externally loaded multi-bolted connections is limited. In response to this statement, our paper deals with the experimental and numerical studies of an asymmetric preloaded and monotone-loaded multi-bolted connection. The scope of the research includes the analysis of the variability of operating forces in the bolts caused by the external load and the analysis of the displacements of the joined elements.

There are many methods of monitoring the changes in bolt forces. Their extensive review has been presented, inter alia, in [23]. One of the most accurate of these is the strain gauge method [22], therefore it has also been implemented in the experimental part of the described research.

2. Research object and research procedure.

The multi-bolted connection tested in the paper is shown in Fig. 1. It consists of two elements joined by means of i M10×1,25 bolts and nuts (for $i = 1, 2, \dots, 7$). To reduce the number of contact joints, washers were not included in the connection. The contact sur-face of the joined elements is inclined by 30 degrees from the vertical, so that the connection can be loaded with compressive and shear forces. The shape of the contact surface is asymmetrical. The joined elements were made of 1,0577 steel. The bolts were made in class 8,8, and the nuts in class 8. A more detailed depiction of the multi-bolted connection is provided in [12].

The research procedure was divided into two stages. In the first stage, the multi-bolted connection was preloaded according to the method and sequence of tightening previously determined experimentally, as the most advantageous due to the final distribution of the bolt forces after the tightening process [12]. The value of the bolts preload F_p was determined as equal to 22 kN based on Eurocode 3 [25] and the analysis of the permissible values of the pressure between the nuts and the lower joined element in the multi-bolted connection. The connection was tightened in three passes, maintaining the sequence shown in Table. In the first pass, the bolts were preloaded to the value of $0{,}2F_p,$ while in the second and third pass to the value of $0{,}6F_p$ and $F_p,$ respectively.

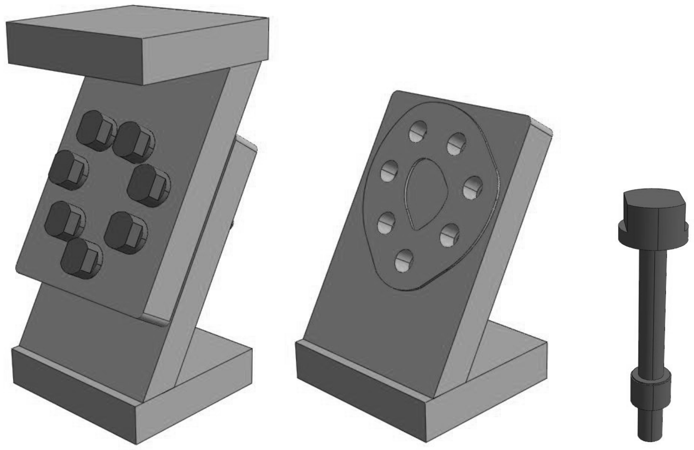
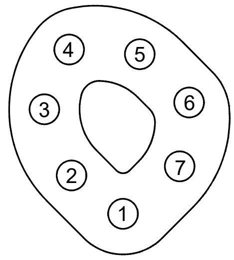


Fig. 1. 3D models of the multi-bolted connection and the single fastener.

Table. Sequence of tightening the multi-bolted connection

Bolt numbering	Sequence
	1-4-7-3-6-2-5

In the second stage, the connection was placed between the heads of the INSTRON 8850 testing machine (Fig. 2) and subjected to the monotonic force F_e, the course of which is shown in Fig. 3.

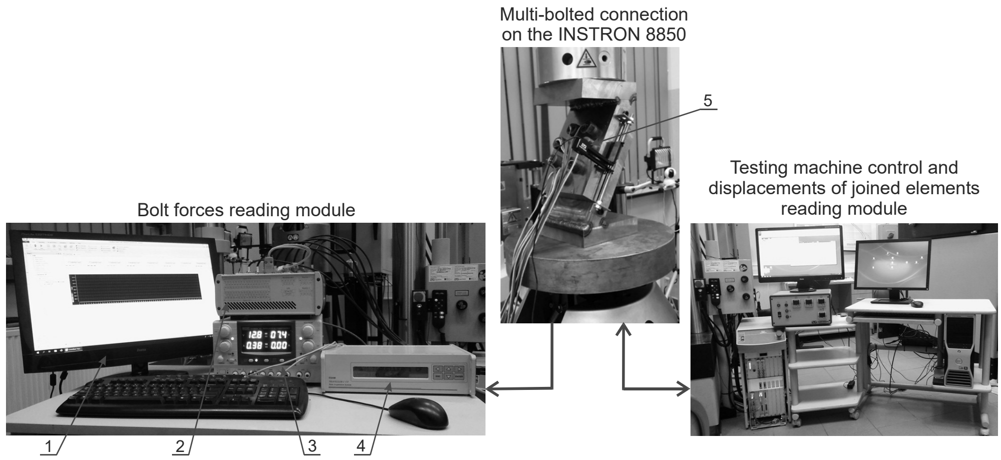


Fig. 2. View of the test stand (1 – Personal Computer, 2 – dSpace MicroLabBox, 3 – MCP lab electronics DC Power Supply, 4 – Esam Traveller 1 CF, 5 – INSTRON extensometer).

The maximum value of the F_e force was selected so that the shear forces caused by it did not exceed the friction forces on the contact surface of the joined elements. Double loading of the connection during a single experiment was related to the study of the influence of the contact nonlinearity occurring during the first loading and unloading on the values of forces in the bolts and displacements of the joined elements. Each experiment was repeated three times, starting with tightening the connection and ending with loading it with the force F_e. The further part of the paper presents the values of bolt forces defined as the arithmetic mean of the data obtained in these experiments.

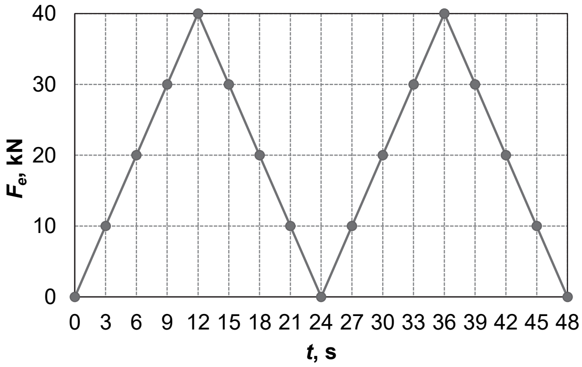


Fig. 3. Course of the external force loading the multi-bolted connection.

Force changes in each bolt were measured with four TENMEX TFxy-4/120 strain gauges, with two perpendicular axes of measurement ladders glued to the bolt in a full bridge arrangement (see [13, 14] for a review). General view of the single bolt used in the multi-bolted connection is shown in Fig. 4. Relative displacements of the joined elements u were measured by means of an extensometer [24].

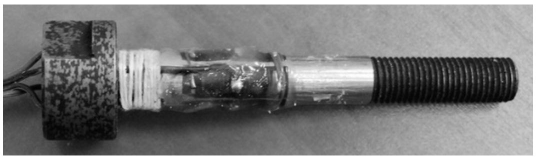
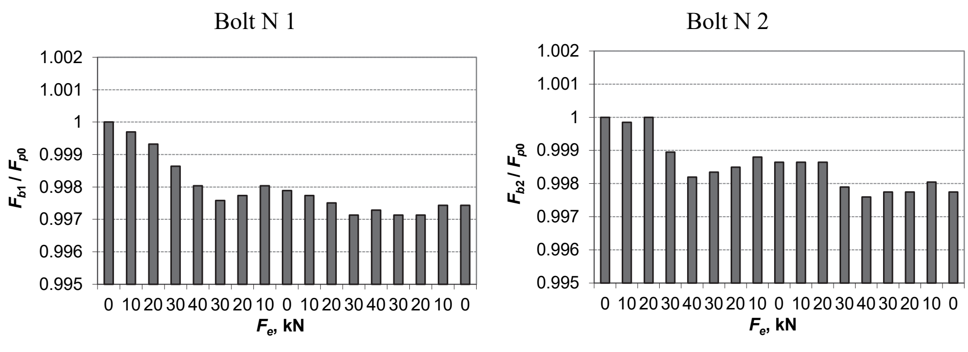


Fig. 4. View of the single bolt used in the multi-bolted connection.

As a result of the variable load on the multi-bolted connection, the forces in the individual bolts also change. The recorded measurements in this range are presented in Fig. 5. It is clearly visible that after the second load, these forces assume lower values than during the



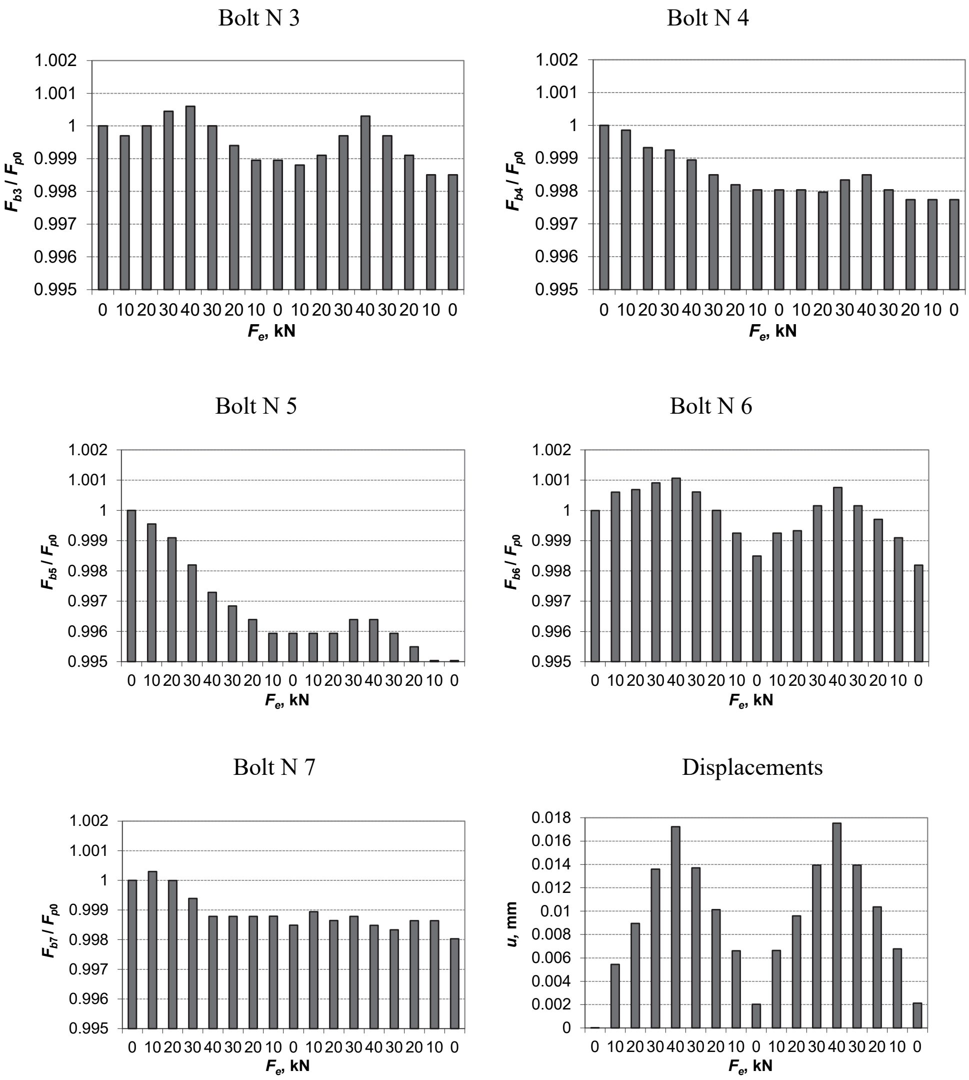


Fig. 5. Distributions of the bolt forces and relative displacements of the joined elements as a function of the exploitation loads.

first load. This shows the influence of the flexibility of the contact layer between the joined elements on the values of the bolt forces and confirms the known phenomenon of reduction of the bolt forces in the connection in the operational state, called the embedding loss [6]. In the case under consideration, the values of the bolt forces at the end of the loading process is lower than thepreload value, but not greater than 1%. It does not cause loss of the load capacity of the connection.

The surfaces of the joined elements were ground before the assembly of the multi-bolted connection. Owing to this fact, the observed relative displacements of the joined elements change linearly in individual cycles of loading and unloading, and the trend lines for them are characterised by the coefficient of determination R^2 ranging from 0,995 to 0,998. The displacement values in the second phase of loading and unloading the connection are only slightly greater than those in the first phase. This slight change is probably caused by the roughness evolution and variability of the surface topography of the joined elements after the first phase of loading and unloading due to relatively low work hardening [20].

3. FEM model of the multi-bolted connection.

As it was shown in the introduction, the finite element method is currently the most popular method of modelling multi-bolted connections. In the models created with this method, the parts joined in the connections are most often modelled using spatial elements [10]. In contrast, the fasteners are modelled in many different ways, which are listed, among others, in the paper [9]. After evaluating the available bolt models, in this paper a deformable beam model with a rigid head and a rigid nut was selected for modelling a single bolt.

The multi-bolted connection model built in the finite element method convention is presented in Fig. 6. Material data of bolts and joined elements as well as the method of tightening and loading the connection are discussed in Section 2. All connection parts were assigned the properties of isotropic linear steel materials. The constitutive relationships in this case can be described by Hooke's law (for comparison, see [11]).

Welded type contact elements were provided between the joined elements and the base plates to prevent the elements from moving in any direction with respect to each other (Fig. 6), according to the actual execution of the connection (Fig. 2).

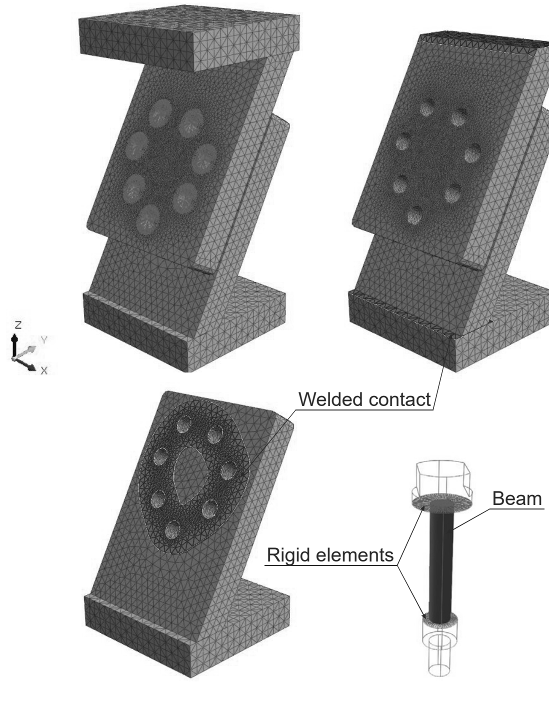


Fig. 6. FEM-based model of the multi-bolted connection.

Welded type contact elements were also inserted between the joined elements. Such procedure in numerical modelling is practiced in the case of preloaded connections [5].

The multi-bolted connection model was created with a sum of 93,283 elements and 157,559 nodes. The maximum dimension of the side length of a finite element in the mesh does not exceed 10 mm. The mesh was significantly densified at the point of contact of the joined elements and at the point of contact of the fasteners and the joined elements.

The connection was fixed by taking away all degrees of freedom on the lower surface of the bottom plate. The calculations were performed in two stages. The first one was performed assuming gradual bolt tightening according to Table and carried out in three passes described in Section 2. In the second stage, the preloaded connection was externally loaded with a force applied in the Z direction distributed evenly over the entire upper surface of the top plate. The course of this force is shown in Fig. 3. The calculations were performed using the sequential nonlinear module, which consists of nonlinear static analysis for the bolt tightening stage and nonlinear implicit transient analysis for the connection operational stage.

4. Comparison of the results of measurements and calculations.

The distributions of the bolt forces and relative displacements of the joined elements as a function of the exploitation loads obtained as a result of measurements and calculations are shown in Fig. 7.

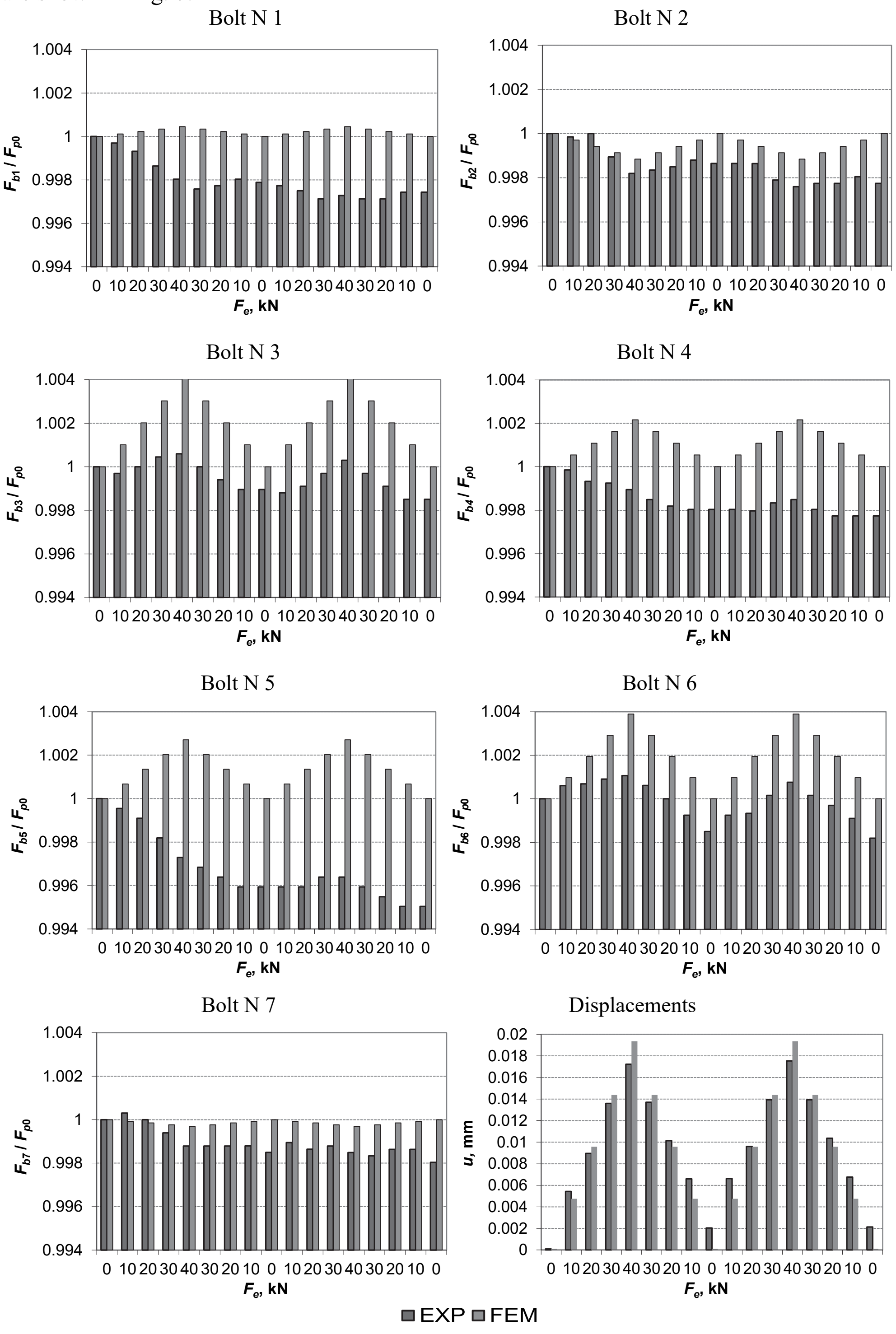


Fig. 7. Distributions of the bolt forces and relative displacements of the joined elements: comparison of the results.

The waveforms obtained from FEM calculations generally agree qualitatively with the results of experimental studies. The adoption of the proposed model results in overstating the value of forces in the bolts by 1% and the value of relative displacements of the joined elements by 13%. The assumption of a rigid contact in the FEM-based model is related to the linear nature of individual plots. Better fit of the waveforms would be possible by taking into account the nonlinearity of the contact layer between the joined elements. It will be the subject of separate publications.

5. Concluding remarks.

The paper presents the experimental and numerical investigations of an asymmetric multi-bolted connection sequentially preloaded and subjected to monotonic normal and tangential loads. Based on these studies, the following conclusions can be drawn:

1. The forces in the individual bolts change as a result of a variable external load of the multi-bolted connection. The experimentally recorded values clearly show that after the second load, these forces take smaller values than during the first load. It shows the influence of the flexibility of the contact layer between the joined elements on the values of the forces in the bolts. In the case under consideration, the reduction of the bolt forces at the end of the loading process does not result in the loss of the load capacity of the connection.

2. Due to grinding the surfaces of the joined elements before the assembly of the multi-bolted connection, a linear variation of the relative displacements of the joined elements was observed in individual loading and unloading cycles.

3. In the case of preloaded multi-bolt connections, operationally loaded with a monotonic force, it is recommended to model the contact layer between the joined elements as a rigid contact. Such a simplification may result in a negligible increase in the value of the forces in the bolts and an acceptable increase in the value of the relative displacements of the joined elements in relation to the actual values.

РЕЗЮМЕ. Представлено експериментальні випробування семиболтового з'єднання з несиметричною площею контакту між з'єднуваними елементами. Дослідження розділено на два етапи. У першому з'єднання попередньо завантажувалося в триходовий цикл. На другому етапі з'єднання навантажувалося монотонним змінним навантаженням, прикладеним під кутом 30 градусів до контактної поверхні з'єднуваних елементів для створення стискаючих і поперечних зусиль у з'єднанні. Експерименти проводились на випробувальній машині INSTRON 8850. У результаті дослідження були показані напруження у болтах, виміряні за допомогою тензодатчиків опору, та відносні переміщення між елементами, що з'єднуються, виміряні екстензометром. У другій частині роботи представлено моделювання методом скінченних елементів. З'єднані елементи моделювали з використанням просторових скінченних елементів, а елементи кріплення – як гібридні елементи з деформівної балки, жорсткої головки та жорсткої гайки. Порівняно результати вимірювань і розрахунків, на підставі яких зроблено висновки, важливі з точки зору скінченно-елементного аналізу.

КЛЮЧОВІ СЛОВА: багатоболтове з'єднання, попереднє навантаження, монотонне навантаження, метод скінченних елементів.

1. *S.B.M. Boudia, N. Boumechra, A. Bouchair, A. Missoum*. "Modeling of bolted endplate beam-to-column joints with various stiffeners", *J. Constr. Steel Res.*, **167**, 105963 (2020).

2. *M. Couchaux, M. Hjiaj, I. Ryan, A. Bureau.* "Tensile resistances of bolted circular flange connections", *Eng. Struct.*, **171**, 817 – 841 (2018).

3. *C. Díaz, P. Martí, M. Victoria, O.M. Querin.* "Review on the modelling of joint behavior in steel frames", *J. Constr. Steel Res.*, **67**, 741 – 758 (2011).

4. *P. Dukalski, B. Będkowski, K. Parczewski, H. Wnęk, A. Urbaś, K. Augustynek.* "Analysis of the influence of motors installed in passenger car wheels on the torsion beam of the rear axle suspension", *Energies*, **15**, N 1, 222 (2022).

5. *M. Giglio, A. Manes.* "Crack propagation on helicopter panel: Experimental test and analysis", *Eng. Fract. Mech.*, **75**, N 3 – 4, 866 – 879 (2008).

6. *H. Gong, X. Ding, J. Liu, H. Feng.* "Review of research on loosening of threaded fasteners", *Friction*, **10**, N 3, 335 – 359 (2021).

7. *M. Gordziej-Zagórowska, E. Urbańska-Galewska, P. Deniziak.* “Experimental investigation of joint with positive eccentricity in CFS truss”, *Thin-Walled Struct.*, **157**, 106998 (2020).
8. *R. Grzejda,* “Finite element modelling of a pair of flexible elements contact preloaded and externally loaded with an arbitrary force”, *Adv. Sci. Technol. Res. J.*, **14**, N 3, 118 – 124 (2020).
9. *R. Grzejda.* “Impact of nonlinearity of the contact layer between elements joined in a multi-bolted system on its preload”, *Int. J. App. Mech. Eng.*, **22**, N 4, 921 – 930 (2017).
10. *R. Grzejda.* “Modelling nonlinear multi-bolted connections: A case of operational condition”. In: Proc. of the 15th Int. Sci. Conf. “Engineering for Rural Development 2016” (Jelgava, Latvia, 25-27 May 2016), Jelgava, Latvia University of Agriculture 2016, 336 – 341.
11. *R. Grzejda.* “Thermal strength analysis of a steel bolted connection under bolt loss conditions”, *Eksploat. Niezawodn. – Maint. Reliab.*, **24**, N 2, 269 – 274 (2022).
12. *R. Grzejda, A. Parus.* “Experimental studies of the process of tightening an asymmetric multi-bolted connection”, *IEEE Access*, **9**, 47372 – 47379 (2021).
13. *R. Grzejda, A. Parus.* “Health assessment of a multi-bolted connection due to removing selected bolts”, *FME Trans.*, **49**, N 3, 634 – 642 (2021).
14. *R. Grzejda, A. Parus, K. Kwiatkowski.* “Experimental studies of an asymmetric multi-bolted connection under monotonic loads”, *Materials*, **14**, N 9, 2353 (2021).
15. *P. Jaszak,* “The elastic serrated gasket of the flange bolted joints”, *Int. J. Press. Vessel Pip.*, **176**, 103954 (2019).
16. *J. Jin, Y. Chen.* “Quality and reliability information integration for design evaluation of fixture system reliability”, *Qual. Reliab. Eng. Int.*, **17**, N 5, 355 – 372 (2001).
17. *P. Kawecki, A. Kozlowski.* “Experimental investigation of end-plate splices with multiple bolt rows of large girders”, *J. Constr. Steel Res.*, **167**, 105859 (2020).
18. *T. Kim, M. Kim, T. Cho.* “Parametric study on ultimate strength of four-bolted connections with cold-formed carbon steel”, *Int. J. Steel Struct*., **18**, N 1, 265 – 280 (2018).
19. *S. Kiyokawa, K. Tateishi, T. Hanji, M. Shimizu.* “Slip coefficient and ultimate strength of highstrength bolted friction joints with compact bolt spacing and edge distance”, *Int. J. Steel Struct.,* **19**, N 4, 1191 – 1201 (2019).
20. *S. Kucharski, G. Starzyński.* “Contact of rough surfaces under normal and tangential loading,” *Wear*, **440-441**, 203075 (2019).
21. *X.C. Liu, X.N. He, H.X. Wang, A L. Zhang.* “Compression-bend-shearing performance of column-to-column bolted-flange connections in prefabricated multi-high-rise steel structures”, *Eng. Struct.*, **160**, 439 – 460 (2018).
22. *P. Majda, J. Jastrzębska.* “Measurement uncertainty of generalized stiffness of machine tools”, *Measurement*, **170**, 108692 (2021).
23. *R. Miao, R. Shen, S. Zhang, S. Xue.* “A review of bolt tightening force measurement and loosening detection”, *Sensors*, **20**, N 11, 3165 (2020).
24. *W. Mucha, W. Kuś, J.C. Viana, J.P. Nunes.* “Operational load monitoring of a composite panel using artificial neural networks”, *Sensors*, **20**, N 9, 2534 (2020).
25. *PN-EN 1993-1-8* (2006), “Eurocode 3: Design of Steel Structures, Part 1-8: Design of Joints”, Polish Committee for Standardization, Warsaw.
26. *K. Puchała, E. Szymczyk, J. Jachimowicz, P. Bogusz, M. Sałaciński.* “The influence of selected local phenomena in CFRP laminate on global characteristics of bolted joints”, *Materials*, **12**, N 24, 4139 (2019).
27. *M. Woch*. “Reliability analysis of the PZL-130 Orlik TC-II aircraft structural component under real operating conditions”, *Eksploat. Niezawodn. – Maint. Reliab.*, **19**, N 2, 287 – 295 (2017).
28. *W. Wuwer, J. Zamorowski, S. Swierczyna.* “Lap joints stiffness according to Eurocode EC3 and experimental investigations results”, *Arch. Civ. Mech. Eng.*, **12**, N 1, 95 – 104 (2012).
29. *G. Xu, Y. Wang, Y. Du, W. Zhao, L. Wang.* “Static strength of friction-type high-strength bolted T-stub connections under shear and compression”, *Appl. Sci.*, **10**, N 10, 3600 (2020).
30. *P. Zampieri, A. Curtarello, E. Maiorana, C. Pellegrino.* “A review of the fatigue strength of shear bolted connections”, *Int. J. Steel Struct.*, **19**, N 4, 1084 – 1098 (2019).

From the Editorial Board: The article corresponds completely to submitted manuscript.

Надійшла 24.09.2022 Затверджена до друку 28.03.2023