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# Experimental Studies of the Process of Tightening an Asymmetric Multi-Bolted Connection

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**ABSTRACT** The paper presents experimental studies of an asymmetric multi-bolted connection at the preloading state. Design assumptions and structure of a stand for testing forces in bolts in a multi-bolted connection were introduced. The tightening process was conducted with a wrench, monitoring the values of the forces in the bolts using a calibrated measuring system based on resistance strain gauges. The measurement data was processed using the Matlab R2018b Simulink program. Two methods of bolt tightening were tested: in one pass (in which the bolts were tightened in a specific sequence and each bolt was tightened immediately to the full preload value) and in several passes (in which the bolts were also tightened sequentially but the full preload value was applied to the bolts in three tightening cycles). The influence of the method and sequence of bolt tightening on the distribution of force values in bolts during and at the end of the preloading state was investigated. The results were statistically processed and summarized in the form of diagrams showing the distributions of normalized force values in the bolts for all the considered tightening cases. The tests were carried out for the selected connection and an assembly method was proposed which would make it possible to achieve the most even distribution of the force values in the bolts at its end, and thus before the connection exploitation state.

**INDEX TERMS** Bolt tightening sequence, multi-bolted connection assembly, preload monitoring, resistance strain gauges.

## I. INTRODUCTION

Multi-bolted connections used as nodes in engineering structures are critical components of many complex systems that play a key role in their integrity and stability. Therefore, their research and analysis are still undertaken by scientists, inter alia, in [1]–[3].

The essence of multi-bolted connections is the occurrence of two states of tension in their case. The first one is the preloading state, which is the subject of the paper and which precedes the second state, i.e. the connection exploitation state. Very often, the preload is necessary for the proper functioning of the connection under operating conditions [4]–[6]. Depending on these conditions, standard bolts or high-strength bolts can be used in preloaded connections. The second of these are made in the following classes of mechanical properties: 8.8, 10.9, and 12.9. In accordance with PN-EN 1993-1-8 standard [7], two systems of high-strength preloadable bolts can be adopted for structural applications in Europe, namely the HR system and the HV system. The characteristics of these systems are presented, among others, in papers [8], [9].

Tightening the bolts is also related to the variability of the preload values in individual bolts during the connection assembly process, and thus with uneven distribution of the preload in the bolts forming the connection at the end of this process [10], [11]. There is also a long-term loss of preloading in the bolts [12]. Taking all these phenomena into account, in many cases, precise tightening of the connection is required in order to obtain the appropriate (sometimes normalized) level of the bolt forces. The following experimental methods are then used to monitor bolt forces or detect loosening:

--Torque wrench method [13]–[15].

--Measurement with the use of resistance strain gauges, both glued to the outside of the bolt [16]–[21] and inserted into the hole inside the bolt shank [22]–[24].

--Ultrasonic detection [25]–[27].

--Application of direct tension indicators [28], [29].

--Acoustic method [30], [31].

--Impedance method [32]–[34].

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In addition to the above-mentioned traditional methods of assessing bolt forces, there are several novel methods. Nazarko and Ziemianski [35] have used the phenomenon of elastic wave propagation, introduced and measured by piezoelectric transducers, to identify the forces in the bolts in a flange connection. The relationships between the measured signal changes and the variations of the forces in the bolts were assessed in this case using artificial neural networks. Sun *et al*. [36] have proposed a bolt-loosening detection method based on the binocular vision. Also, a vision-based method for the bolts looseness detection has been shown by Wang *et al*. [37].

The conducted review shows that currently there are many methods of monitoring bolt forces and detecting loosening in bolted connections. In order to select the appropriate test method, one can take into account the costs and accuracy associated with it [38]. The most popular method of measuring bolt forces is the method based on the use of resistance strain gauges. In addition to ultrasonic sensing, it is the method with the highest accuracy [35]. Therefore, this method has been also implemented in the presented paper.

Until now, experimental studies of the tightening process of multi-bolted connections have been carried out mainly for connections showing geometric symmetry. In these works, both tightening in one pass [39], [40] and in several passes were considered [41], [42]. Therefore, the aim of the presented paper was to compare the above-mentioned methods of bolt tightening. Additionally, in order to add an element of universality to the tests, they were performed for the case of an asymmetric multi-bolted connection. The research described in this paper will be used to verify the modeling method of the tightening process of arbitrary multi-bolted connections presented in [43], [44].

## II. RESEARCH STAND

Before starting the creation of the test stand, the following assumptions were taken into account:

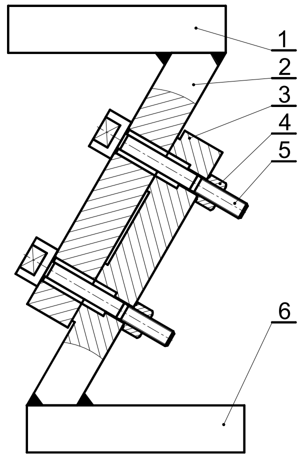
--Stand will only be used to measure the force values in the bolts.

--External dimensions of the entire connection will be selected based on the analysis of the sizes of available strain gauges and the corresponding required dimensions of cylindrical surfaces on the shank of bolts used in the connection.

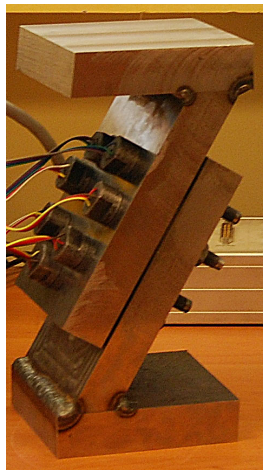
--Elements will be joined by an odd number of bolts.

--Connection will be characterized by an asymmetric contact surface between the joined elements.

Taking into account the above-mentioned assumptions, a multi-bolted connection was design and built, the diagram of which is shown in Fig. 1. The tested connection consists of two plates (2) and (3) with a thickness of 28 mm, fastened with seven M10x1.25 bolts (5) tightened by high hexagonal nuts (4). The connection is inclined from the vertical by 30 deg. The plate (2) is welded to the upper plate (1) and the plate (3) to the base (6). The height of the test stand is 266 mm. All joined elements are made of 1.0577 steel. The bolts are made in the mechanical property class 8.8, and the nuts in the mechanical property class 8. In order to minimize the hysteresis phenomenon during calibration, the bolts have been heat treated. However, to minimize the influence of the number of contact joints in the multi-bolted connection on the accuracy of the modeling of the tightening process (planned at a later date), washers were not included in the connection. The fasteners used in the test cannot be classified according to the PN-EN 1993-1-8 standard [7], as it does not provide for M10 bolt systems without washers. They are special bolt-nut systems and will be used to validate the bolt modeling method described in [45].




(a) Diagram



(b) General view

**FIGURE 1.** Tested multi-bolted connection (1 – upper plate, 2,3 – joined plates, 4 – high hexagonal nut, 5 – M10x1.25 bolt, 6 –base).

The structure of the multi-bolted connection described in the paper is to enable testing of this connection under the influence of external loads directed at a given angle in relation to the contact plane of the joined elements using the INSTRON 8850 testing machine.

The contact surface between the joined elements is shown in Fig. 2. The area of this surface is limited by a circle with a diameter of 175 mm. Its size is less than 143 cm$^2$ and does not exceed the required pressure limit for 1.0577 steel.

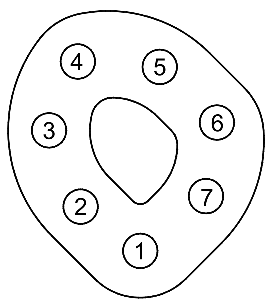



**FIGURE 2.** Diagram of the contact surface between the joined elements.

The bolts in the connection have been arranged according to the recommendations given in the PN-EN 1993-1-8 standard [7]. The force changes in each bolt were measured using four TENMEX TFxy-4/120 strain gauges, with two axes of measuring ladders arranged perpendicularly to each other, glued to the bolt in a full strain gauge bridge system. The view of the bolts is shown in Fig. 3.

**FIGURE 3.** View of the bolts.

The reading and processing of experimental data was performed with the use of the measuring system, the view of which is shown in Fig. 4.

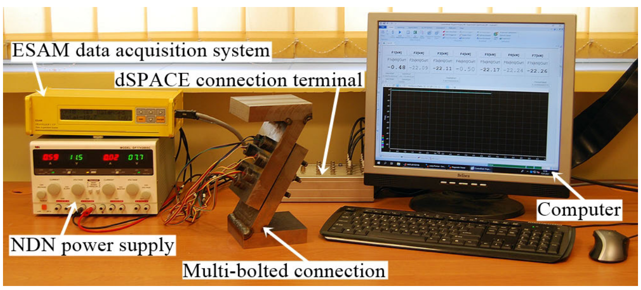



**FIGURE 4.** View of the research stand.

On the described stand, it is possible to conduct a wide program of experimental studies, including, inter alia, testing of a multi-bolted connection in the preloading state at different values of the preload and with various methods of tightening.

## III. RESEARCH PROCEDURE

The value of the bolts preload was determined as equal to 22 kN based on the PN-EN 1993-1-8 standard [7] and the analysis of the permissible values of the pressure between the nuts and the lower joined element. The process of tightening the multi-bolted connection was carried out for two assembly methods: in one pass and in three passes. The comparison of these methods is summarized in Table 1.

In each of the methods mentioned in Table 1, tests were performed with the six different tightening sequences shown in Table 2. Each experiment was repeated three times. In the further part of the paper, the values of bolt forces defined as the arithmetic mean of the data obtained in these experiments are presented.

## IV. RESEARCH RESULTS

The distributions of the mean values of forces $F_{pi}$ in the bolts related to the value of the initial force $F_{p0}$ during tightening the multi-bolted connection in one pass is shown in Fig. 5. Analogous diagrams for the case of tightening the connection in three passes are presented in Fig. 6.

Based on the analysis of the graphs in Figs. 5 and 6, the following conclusions can be drawn:

1) The value of the bolt tightening force may change after applying the preload to successive bolts.
2) The variability of the bolt forces value during the assembly depends on the bolt tightening sequence. The influence of this phenomenon can be reduced by tightening the multi-bolted connection in several passes.
3) The greatest decrease in force in a given bolt occurs after tightening the bolt located in the immediate vicinity (e.g., the greatest decrease in force in the bolt No.1 occurs after tightening bolts No. 2 and 7).
4) During tightening a multi-bolted connection, tightening consecutively two bolts in the immediate vicinity of the previously preloaded bolt should be avoided (in this

**TABLE 1.** Methods of tightening the multi-bolted connection.

| Symbol | Quantity [a] | Value |
|---|---|---|
| | Tightening in one pass | |
| $F_{pi}$ | preload of the *i*-th bolt | $F_{pi} = 22$ kN |
| | Tightening in three passes | |
| $F_{pi1}$ | preload of the *i*-th bolt in the first pass | $0.2 \cdot F_{pi} = 4.4$ kN |
| $F_{pi2}$ | preload of the *i*-th bolt in the second pass | $0.6 \cdot F_{pi} = 13.2$ kN |
| $F_{pi3}$ | preload of the i-th bolt in the third pass | $F_{pi} = 22$ kN |

[a] $i = \{1, 2, \ldots, 7\}$.

**TABLE 2.** Sequences of tightening the multi-bolted connection.

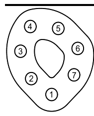
| Type | | Sequence |
|---|---|---|
|  | 1 – tightening the bolts sequentially to the right | 1-2-3-4-5-6-7 |
| | 2 – tightening every second bolt in a row | 1-3-5-7-2-4-6 |
| | 3 – tightening every third bolt in a row | 1-4-7-3-6-2-5 |
| | 4 – tightening every fourth bolt in a row | 1-5-2-6-3-7-4 |
| | 5 – tightening every fifth bolt in a row | 1-6-4-2-7-5-3 |
| | 6 – tightening the bolts sequentially to the left | 1-7-6-5-4-3-2 |

**TABLE 3.** *Z* index values (%).

| Type | Tightening in one pass | Tightening in three passes |
|---|---|---|
| 1 | 1.06 | 0.45 |
| 2 | 2.07 | 0.48 |
| 3 | 1.14 | 0.42 |
| 4 | 1.16 | 0.43 |
| 5 | 1.23 | 0.54 |
| 6 | 0.94 | 0.42 |

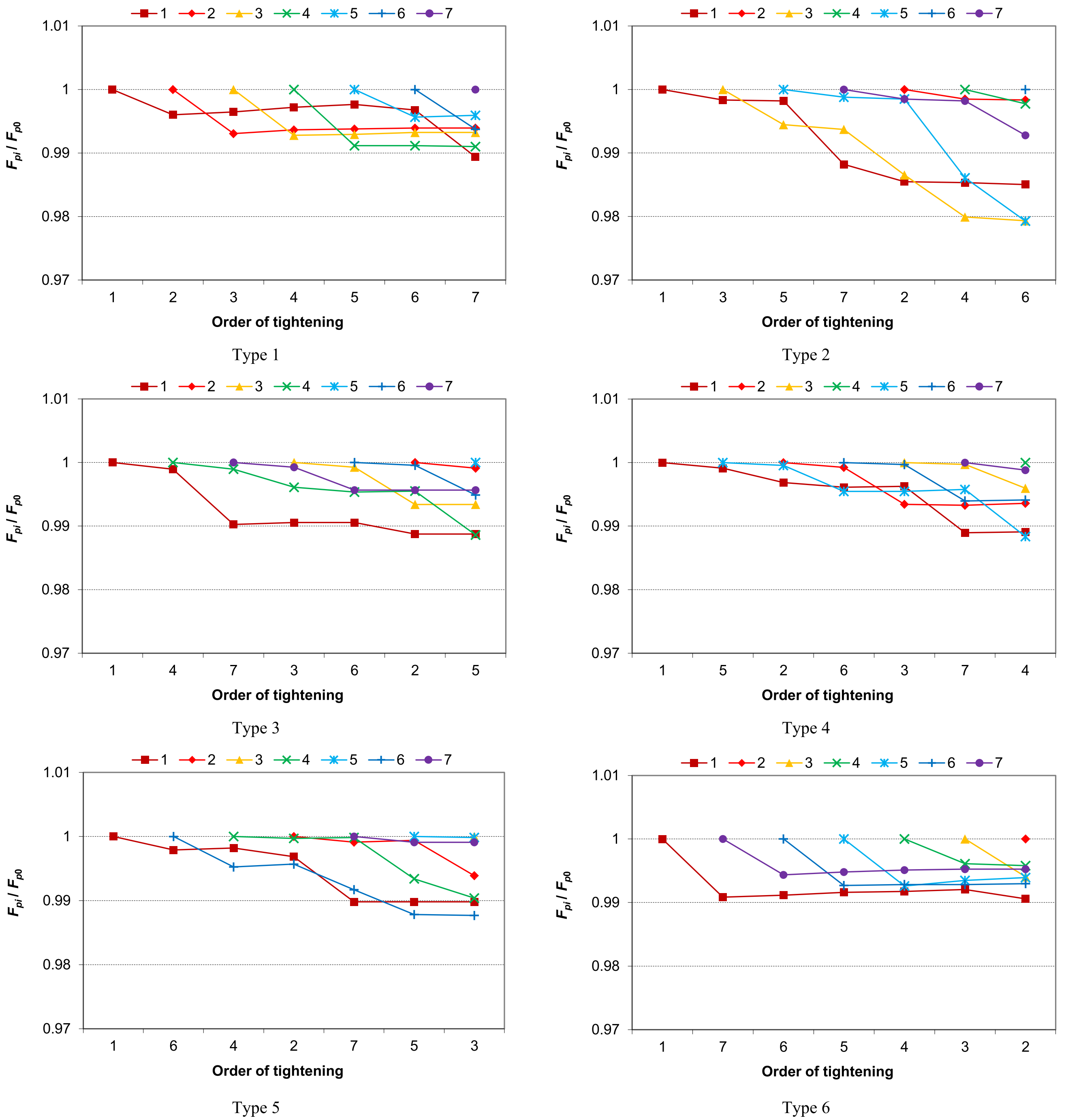



**FIGURE 5.** **Distributions of the bolt forces during tightening the connection in one pass.**

case two steps follow each other with the greatest force drops in the previously preloaded bolt, an example of which is tightening according to type 2).

The distributions of the mean values of forces $F_{pi}$ in the bolts related to the value of the initial force $F_{p0}$ at the end of tightening the multi-bolted connection, depending on the method of performing the tightening process, are presented in Fig. 7.

Based on the analysis of the graphs in Fig. 7, the following conclusions can be drawn:

1) The distributions of the preload in individual bolts at the end of the assembly of the multi-bolted connection may be characterized by some unevenness.
2) The variability of the bolt force value at the end of the assembly depends on the bolt tightening sequence. The influence of this phenomenon can be reduced

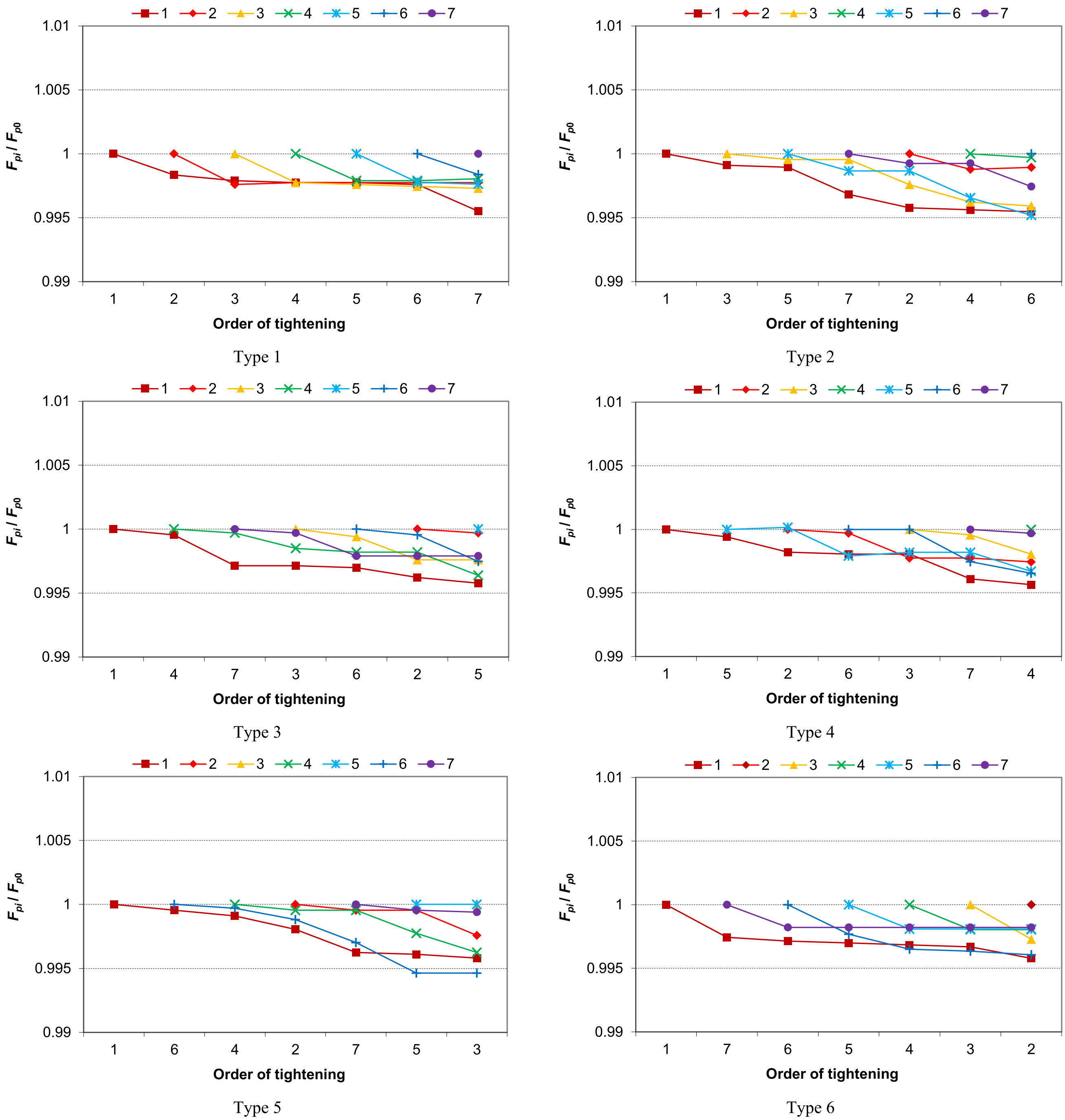



**FIGURE 6. Distributions of the bolt forces during tightening the connection in three passes.**

by tightening the multi-bolted connection in several passes.

The comparative analysis of the waveforms presented in Fig. 7 was carried out on the basis of the $Z$ index defined as:

$$Z = \left| \frac{F_{pi}^{max} - F_{pi}^{min}}{F_{pi}^{max}} \right| \cdot 100 \tag{1}$$

where $F_{pi}^{max}$ denotes the maximum mean value of the bolt force in the considered distribution of forces after the tightening process, and $F_{pi}^{\min}$ denotes the minimum mean value of the bolt force in the considered distribution of forces after the tightening process.

The $Z$ index values obtained for individual tightening methods are presented in Table 3. Based on its analysis, the following conclusions can be drawn:

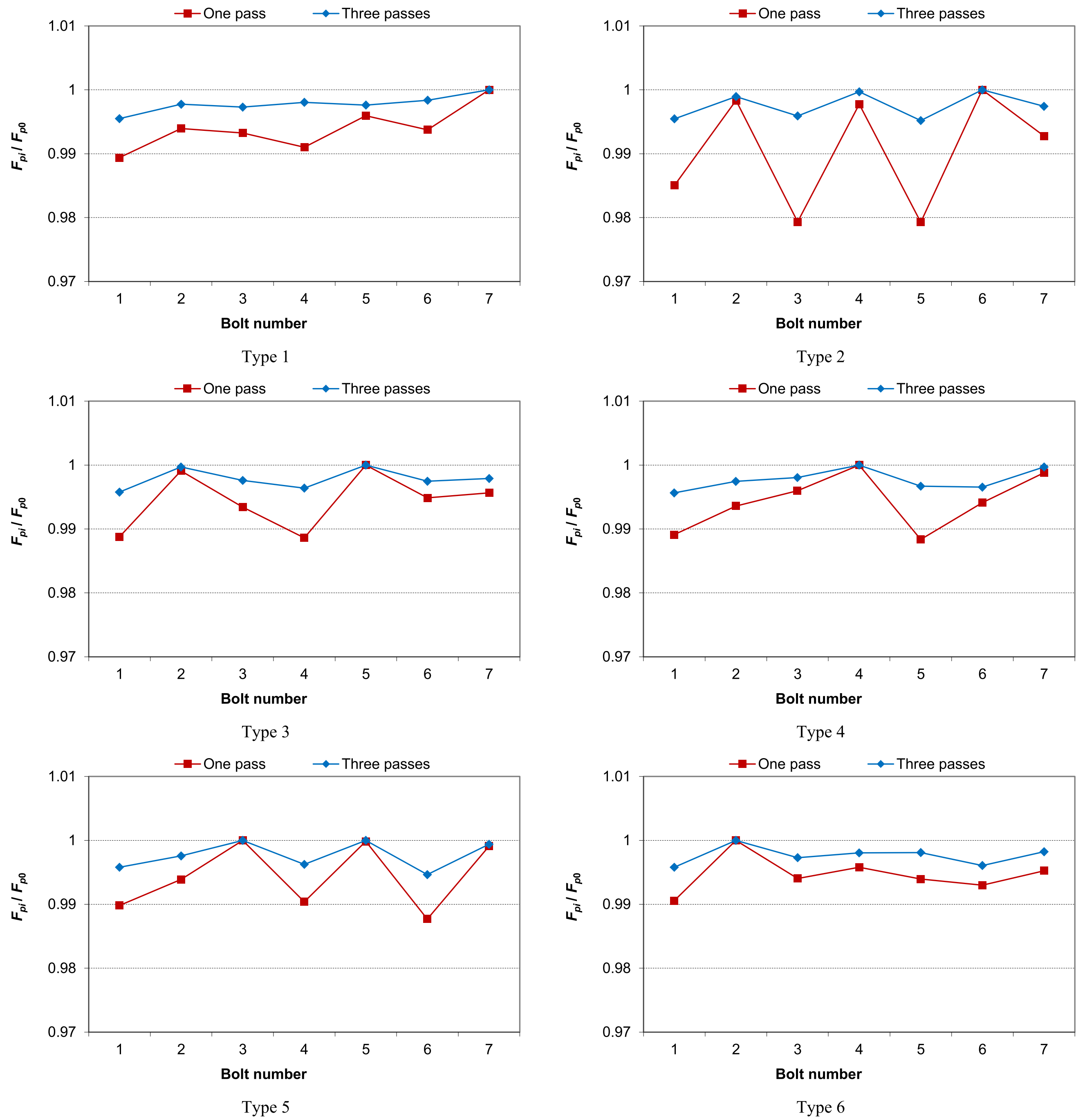



**FIGURE 7.** **Distributions of the bolt forces at the end of tightening the connection.**

1) Tightening bolts in several passes leads to a more even distribution of bolt forces compared to tightening in one pass.
2) In the case of some connections (such as the considered several-bolted connection), tightening the bolts sequentially may lead to a relatively even distribution of bolt forces at the end of the tightening process.
3) The method of bolt tightening according to type 3 in three passes is recommended as the best among the tested methods of tightening.

## V. CONCLUSION

In the paper, an original laboratory stand intended for testing a selected asymmetric multi-bolted connection is presented. The tests were carried out under the conditions of initial tightening the connection. Guidelines for planning the preloading operation of multi-bolted connections are given. They ensure the smallest scatter of preload after tightening the bolts. The stand can be used for further studies in the field of external loading of the connection.

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