DOI:10.22337/2587-9618-2025-21-4-162-176

STRESS-STRAIN STATE OF SLIP-CRITICAL CONNECTIONS IN METAL STRUCTURES, WITH REGARD TO THE SPECIFICS OF BOLT TENSION CONTROL

Andrey A. Vasilkin, Georgiy V. Zubkov

National Research University Moscow State University of Civil Engineering, Moscow, RUSSIA

Abstract: The load-bearing capacity of a slip-critical connection depends on two factors: the bolt tension force and the friction coefficient between the coupled surfaces. Reliably achieving the specified tension force is necessary to guarantee the design performance of the connection. A number of methods for accomplishing this task are known, but only one of them is sufficiently well regulated and used in practice – the torque method.

This article analyzes the requirements and guidelines of foreign and domestic regulatory documents, research conducted in this area in the construction industry and adjacent fields, and identifies the most reasonable methods for further study of bolt tension control.

An analytical model of the stress-strain state of a slip-critical connection is proposed, and the relationship between the bolt tension force and the nut rotation angle is determined. The results obtained are compared with the recommendations of foreign regulations.

An experimental study of the tensioning process for high-strength bolt sets of various diameters – M16, M20, and M24 – has been carried out. The relationships between the nut rotation angle, torque, and tension in the bolt body were described and analyzed. The obtained data were compared with the proposed calculation model. The nut rotation angles that allow the design bolt tension force to be achieved were established.

Keywords: slip-critical connection, bolted joint, bolt pretensioning, high-strength bolts

НАПРЯЖЕННО-ДЕФОРМИРОВАННОЕ СОСТОЯНИЕ ФРИКЦИОННЫХ СОЕДИНЕНИЙ МЕТАЛЛИЧЕСКИХ КОНСТРУКЦИЙ С УЧЕТОМ ОСОБЕННОСТЕЙ КОНТРОЛЯ НАТЯЖЕНИЯ БОЛТОВ

А.А. Василькин, Г.В. Зубков

Национальный исследовательский Московский государственный строительный университет, г. Москва, РОССИЯ

Аннотация: Несущая способность сдвигоустойчивого соединения зависит от двух величин: усилия натяжения болта и коэффициента трения между соединяемыми поверхностями. Надежное обеспечение заданного усилия натяжения необходимо для того, чтобы гарантировать проектную работу соединения. Известно несколько способов решения этой задачи, однако в настоящее время достаточно полно регламентирован и используется на практике только один – по моменту закручивания.

В данной статье проанализированы требования и указания зарубежной и отечественной нормативной документации, исследования, проведенные в этой области в строительной сфере и в смежных областях, выделены наиболее рациональные для дальнейшего изучения методы контроля натяжения болтов.

Предложена аналитическая модель напряженно-деформированного состояния болтового фрикционного соединения, определена зависимость усилия натяжения болта от угла поворота гайки. Полученные результаты сопоставлены с рекомендациями зарубежных норм.

Выполнено экспериментальное исследование процесса натяжения высокопрочных болтокомплектов различных диаметров – M16, M20 и M24. Описаны и проанализированы зависимости между углом поворота гайки, крутящим моментом и усилием в теле болта. Проведено сравнение полученных данных с предложенной расчетной моделью. Установлены углы поворота гайки, позволяющие достичь расчетного усилия натяжения болта.

Ключевые слова: фрикционное соединение, болтовое соединение, преднапряжение болтов, высокопрочные болты

INTRODUCTION

Slip-critical connections with pretensioned bolts are widely used in construction. The specific features of this type of connection, which involve the transfer of forces by means of friction, ensure reliability and high fatigue resistance of the connection under various types of loads and stresses, including seismic, dynamic, and vibrational. Currently, research is being conducted in the domestic scientific community and abroad to study various factors affecting the load-bearing capacity of joints [1...8].

One of the main conditions for achieving the design load capacity of a slip-critical connection is to ensure sufficient bolt pretension. Currently, two methods of pretension control are described in the normative documentation applicable: by tightening torque and by nut rotation angle. The method of controlling the pretension force by moment of tightening has been sufficiently researched and is widely used in practice. In turn, the method of controlling the pretension force by nut rotation angle has not been fully researched, and there are no guidelines for its use for a wide range of bolt diameters. It ensures that the design tension force is achieved in the fasteners used to execute the connection with a higher degree of reliability, and eliminates the influence of the tightening coefficient on tension force, which allows increasing the load-bearing capacity of the connection [10, 15, 16].

The purpose of this study is, firstly, to analyze the methods of pretension control used in international construction practice and related industries, the application of which can improve the reliability of controlled-tension bolted connections, increase labor productivity in the assembly of metal structures, and reduce the cost of their installation.

Secondly, the aim is to describe the stress-strain state of a friction connection during bolt tensioning. Research into this process has been undertaken previously, for example in [12], but most of the relationships proposed were empirical. An analytical description of the performance of different connection elements during bolt tensioning will allow for experimental and numerical studies of the method of controlling bolt tension by angle of rotation and for the development of recommendations for its use, thereby increasing the load-bearing capacity of friction connections in metal building structures.

Thirdly, to confirm the hypotheses adopted in the formation of the calculation model of the stress-strain state of the connection, it is necessary to conduct an experimental study, describe and analyze the dependencies between the nut rotation angle, torque, and tension in the bolt body, compare them with the proposed calculation model and with the values obtained by other researchers and recommended in foreign and domestic documentation. The result of the work should be recommendations that allow the use of various methods of controlling bolt tension and identified directions for further research.

METHODS

The article analyzes the requirements of domestic and foreign regulatory documents regarding methods for controlling bolt pretension, domestic and foreign research on this topic, and identifies the most promising methods for further study of controlling the pretension of bolts in shear-resistant connections.

Stress-strain state mathematical models of shear-resistant joints proposed in previous studies are analyzed. Research experience and calculation methods in related disciplines, such as mechanical engineering, are examined and applied to analyze joints used in construction. The theoretical values of the nut rotation angle required to achieve the design bolt tension in the joint are calculated, and methods for determining the initial reference point of the nut rotation angle are analyzed.

During the experiment, 15 bolt sets with diameters of M24, M20, and M16 (5 samples of each diameter) of strength class 10.9 according to GOST R 52644-2006 were tensioned. The thickness of the package formed by the testing setup described below was 110 mm for all bolt set diameters.

The bolt tensioning setup is shown in Figure 1. It consists of a 260x260 mm, 30 mm thick support plate made of C345 steel, which is attached to a solid fixed base with four M20 bolts of strength class 10.9 according to GOST R 52644 -2006 through steel spacers made of C245 steel, which provide the necessary distance from the bottom of the support plate to the base surface for the bolt head to be placed. Three plates with different central hole diameters were manufactured for the experiment, which made it possible to test bolts of three different diameters. For testing M24 bolts, the hole diameter is 26 mm, for testing M20 bolts – 22 mm, and for M16 bolts – 18 mm. The drawing of the support plate for the M24 bolt is shown in Figure 2.

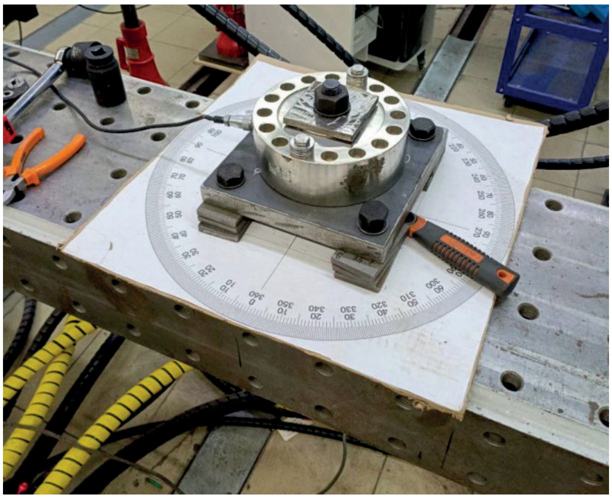

Figure 1. Testing setup

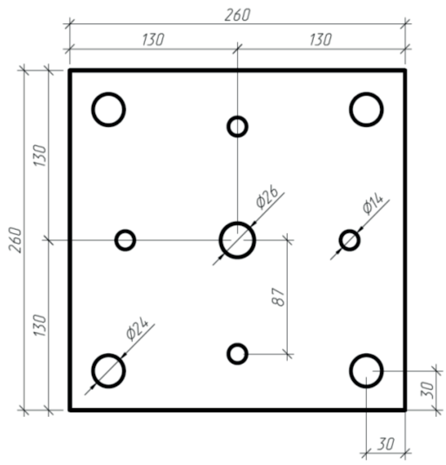

Figure 2. Support plate for the M24 bolt

A calibrated load cell capable of measuring forces in the range from 0 to 500 kN is attached to the base plate with two M12 bolts. A 95x95 mm distribution plate with a thickness of 10 mm, made of C245 steel, is installed on the upper surface of the load cell. Three distribution washers with different central hole diameters were manufactured for the experiment. The hole diameter is 26 mm for testing M24 bolts, 22 mm for testing M20 bolts, and 18 mm for testing M16 bolts. The drawing of the distribution washer for the M24 bolt is shown in Figure 3.

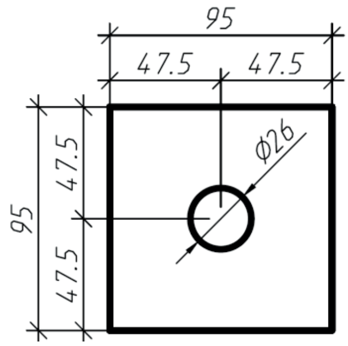

Figure 3. Distribution washer for the M24 bolt

Preparation for the bolt pretensioning procedure was carried out in accordance with the instructions of SP 70.13330.2012. Bolts, nuts, and washers were deconserved by washing them in a mixture consisting of 70-75% unleaded gasoline and 30-25% mineral oil. After deconservation, the threads of the bolts and nuts were lubricated with mineral oil in accordance with GOST R 51634.

The bolt set was installed in the assembled unit. Washers of the appropriate diameter were placed under the bolt head and nut. The bolt head was secured against movement.

The first step in testing the bolt set was to tighten the nut by hand, without using tools. The nut was screwed onto the bolt thread with the fingers, applying as much force as possible.

Two torque wrenches were used to tighten the bolt. The first, with a handle length of 0.5 m, was used to tighten the bolt to a torque of up to 400 N*m. The second, with a handle length of 2 m, was used to tighten the bolt to a torque of more than 400 N*m. Before the experiment, the wrenches were calibrated in accordance with the procedure described in GOST 33530-2015. Further tightening of the bolt was carried out in accordance with the following algorithm:

1. Setting the required torque value on the torque wrench;
2. Fixing the initial angle between the wrench handle and the reference point on a specially designed dial;

In the first tensioning step, the initial angle value was fixed as the force in the bolt increased from a starting value of 0.6–0.9 kN to 1–2 kN. In the steps following the first, the initial angle was taken to be equal to the previous final one if the tensioning was performed without repositioning the wrench handle. If the wrench handle was repositioned between steps, a force equal to that applied in the previous step was applied to the wrench handle to measure the initial angle, and the initial angle was measured with the wrench in the “tensioned” position;

3. Tensioning the bolt to the torque setting on the wrench. Tensioning was performed smoothly, without sudden movements;
4. Measuring the final angle between the wrench handle and the angle measuring axis. The final angle was recorded when the wrench was in the “tension” position, with a force applied to the wrench handle corresponding to the required torque;
5. Measuring the force in the bolt after tightening to the torque set on the wrench.

In this way, the bolt tightening process was broken down into steps, each of which recorded the torque applied to the nut, its angle of rotation relative to the starting position, and the force in the bolt. The torque increase step was selected so that the calculated torque, determined in accordance with the instructions of SP 70.13330.2012 at a tightening coefficient of 0.17, was achieved in 10 steps. The calculated forces for bolt sets were determined in accordance with the instructions of SP 16.13330.2017.

The design force for M24 bolt sets of strength class 10.9 is 257.0 kN, for M20 bolt sets – 178.4 kN, for M16 bolt sets – 114.3 kN. The design torque for M24 bolt sets is 1048.5 N*m, for M20 bolt sets – 606.4 N*m, and for M16 bolt sets – 310.8 N*m.

The tested bolt set specimens are shown in Figure 4.

Figure 4. Bolt set specimens

RESULTS AND DISCUSSION

The test results shown below were compared with the values specified in the standards of the Russian Federation (SP 70.13330.2012 Load-bearing and enclosing structures), the United States (RCSC Specification for Structural Joints Using High-Strength Bolts 2020), the European Union (BS EN 1090-2:2018 – Execution of steel structures and aluminum structures) and Canada (CSA S16-09 – Design of steel).

The reference point for the nut rotation angle when using the single-stage rotation angle control method is not clearly defined in foreign standards, however, SP 70.13330.2012 specifies the torque at which the angle measurement can be started – 176.4...240.1 N*m, with an average of 207.0 N*m. This value is 207.0/1148.5 = 0.18

of the design torque value at a tightening coefficient of 0.17. There are no recommendations for determining the initial torque for bolt sets of other diameters in the normative documentation, so we will assign the torque at which the nut rotation angle is counted to be proportional to the calculated torque with a tightening coefficient of 0.17. Then, for bolt sets with a diameter of M20, it will be equal to 606.4*0.18 = 109.15 N*m, and for bolt sets with a diameter of M16, it will be equal to 310.8*0.18 = 55.9 N*m. Due to the characteristics of the experimental setup, we will round the values to 200, 100, and 60 N*m, respectively.

The standard values for nut rotation angles are given in Table 1.

Table 1. Standard values for nut rotation angles

d	Grip thickness	RCSC 2020	CSA S16-24
M16	t<4d	120+60	120±30
	4d<t<8d	180+60	180±30
	t>8d	240+60	240±30
M20	t<4d	120+60	120±30
	4d<t<8d	180+60	180±30
	t>8d	240+60	240±30
M24	t<4d	120+60	120±30
	4d<t<8d	180+60	180±30
	t>8d	240+60	240±30

Table 1(cont.). Standard values for nut rotation angles, SP 70.13330.2012

d	Grip thickness	SP 70.13330.2012
M16	-	-
	-	-
	-	-
M20	-	-
	-	-
	-	-
M24	40…140 (1,7…5.8d)	180±30

A comparison was also made with the combined method described in BS EN 1090-2:2018. When using this method, in the first stage of pre-tensioning, the bolt set is tightened to a torque equal to 0.75 of the design torque. In the second stage, the nut of the bolt set is turned to a specific angle.

The torque of the first stage for a bolt set with a diameter of M24 is 557 N*m, for a bolt set with a diameter of M20 – 322 N*m, and for a bolt set with a diameter of M16 – 165 N*m. We shall round these figures to 600, 300, and 150 N*m.

The rotation angles recommended by the combined method described in BS EN 1090-2:2018 are shown in Table 2.

Table 2. Standard values for nut rotation angles for combined method, EN 1090-2:2018

d	Grip thickness	EN 1090-2:2018
M16	t<2d	60
	2d<t<6d	90
	t>6d	120
M20	t<2d	60
	2d<t<6d	90
	t>6d	120
M24	t<2d	60
	2d<t<6d	90
	t>6d	120

It should be noted that the approach used in conducting the experiment made it possible to compare the values obtained as a result of tensioning the same sample with the values regulated by various methods.

The analytical model of the connection was formulated based on the following hypotheses:

- the joint components fit tightly together, their geometry is close to ideal;
- A certain angle of rotation of the nut corresponds to a certain displacement, depending on the thread pitch;
- By determining the nut rotation angles corresponding to the deformations of various parts of the connection, it is possible to determine the total angle required to achieve the specified force.

The angle of rotation of the nut and the displacement caused by this rotation are related by the following relationship:

$$\frac{\Delta l}{s} = \frac{\varphi}{360°} \quad (1)$$

The following values were identified as components of the total nut rotation angle:

$$\varphi = \varphi_{б} + \varphi_{р} + \varphi_{гб} + \varphi_{д}, \quad (2)$$

where: φ – nut rotation angle required to create the design bolt tension;
$\varphi_{б}$ – nut rotation angle corresponding to the displacement caused by the elongation of the bolt;
$\varphi_{р}$ – nut rotation angle corresponding to the displacement caused by thread deformation;
$\varphi_{гб}$ – nut rotation angle corresponding to the displacement caused by deformation of the bolt head;
$\varphi_{д}$ – nut rotation angle corresponding to the displacement caused by the flexibility of the joint components.
The design force in a bolted connection, in accordance with the requirements of the normative documentation, is taken to be equal to:

$$P = 0{,}7A_{bn}R_{bun},$$

Then the nut rotation angle corresponding to the displacement caused by the bolt elongation, if the deformable part of the bolt is equal to the grip thickness:

$$\varphi_{б} = 360\frac{t \cdot 0{,}7R_{bun}}{E \cdot s}, \quad (3)$$

However, the research [9] has shown that the strained part of the bolt, where axial stresses occur, includes several threads inside the nut in addition to the thickness of the package. In Figure 5, it is marked asL_e.

$$L_e \approx t + 3 \cdot s;$$

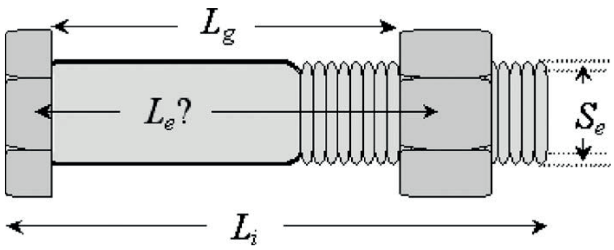

Figure 5. Scheme of bolt assembly under preload, according to [9]

Therefore:

$$\varphi_{б2} = 360\frac{(t + 3 \cdot s) \cdot 0{,}7R_{bun}}{E \cdot s}, \quad (4)$$

The results of the.$\varphi_{б}$ calculation are shown in Figure 6.

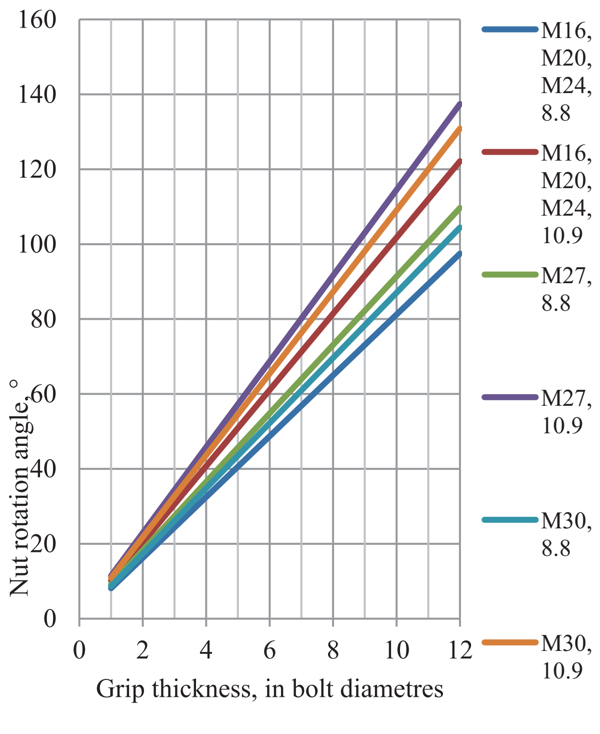

Figure 6. Nut rotation angle corresponding to the displacement caused by the elongation of the bolt

In [12], required rotation angles were calculated assuming that the bolt head and thread are not flexible; however, this approach cannot be considered entirely correct. In mechanical engineering [11, 13, 14], relationships have been established for determining the deformations of these parts of the connection during tightening.

In [13], a relationship is proposed for determining the flexibility of the thread during bolt tightening. By deriving the angle of rotation of the nut corresponding to the displacement caused by thread deformation, we receive:

$$\varphi_{\text{р}1} = \frac{0{,}49 \cdot 360 \cdot 0{,}7 A_{bn} R_{bun}}{d_2 E s} \cdot \sqrt{1{,}44 + 9{,}28 \frac{s}{d}}, \tag{5}$$

where d_2 – average thread diameter

The same source suggests an alternative method for determining thread flexibility: when calculating bolt flexibility, increase its tensile strength by 1/3 to 1/2 of the nut height.

$$\varphi_{\text{р}2} = 360 \frac{0{,}28d \cdot 0{,}7 R_{bun}}{\text{E}s}; \tag{6}$$

However, experimental studies have shown that these equations significantly overestimate thread stiffness, which doesn't match up with experimental data. In [14], an alternative equation for thread flexibility was proposed, allowing for a more accurate determination. When using this relationship, the nut rotation angle is:

$$\varphi_{\text{р}3} = \frac{360 \cdot 0{,}7 A_{bn} R_{bun} \cdot (0{,}8 - 12{,}04d) \cdot 10}{s} \tag{7}$$

The results of the calculations utilizing equation 7, which more closely matches the experimental data, are presented in Table 3.

In addition to thread deformation, bolt head deformation must also be taken into account. To account for its flexibility, it is possible to assume that the bolt head only experiences shear deformation. In this case, the nut rotation angle corresponding to the displacement caused by bolt head deformation will be:

$$\varphi_{\text{гб}} = \frac{0{,}15 \cdot 360 \cdot 0{,}7 A_{bn} R_{bun}}{Ehs} \tag{8}$$

Table 3. Nut rotation angle corresponding to the displacement caused by thread deformation

8.8		10.9	
Bolt diameter	$\varphi_{\text{р}3}$, °	Bolt diameter	$\varphi_{\text{р}3}$, °
M16	9,97	M16	12,50
M20	11,46	M20	14,36
M24	12,58	M24	15,76
M27	15,20	M27	19,04
M30	14,71	M30	18,43

The results of the calculation are shown in Table 4.

Table 4.Nut rotation angle corresponding to the displacement caused by deformation of the bolt head

8.8		10.9	
Bolt diameter	$\varphi_{\text{гб}}$, °	Bolt diameter	$\varphi_{\text{гб}}$, °
M16	1,20	M16	1,50
M20	1,19	M20	1,50
M24	1,19	M24	1,50
M27	1,37	M27	1,72
M30	1,31	M30	1,64

Finally, a significant portion of the deformations in the joint occur in the components of the joint itself. The main issue in calculating these deformations is determining the area of the compressed part of the component. For small joint thicknesses, it can be assumed that this area can be taken as equal to the cross-sectional area of a cylinder with a circular cutout, the outer diameter of which is equal to the size of the bolt under the wrench S, and the diameter of the cutout is equal to the diameter of the bolt hole. Assuming the diameter of the bolt hole $d_0 = d + 2$, we obtain:

$$\varphi_{д1} = \frac{4 \cdot 360 \cdot t \cdot 0{,}7 A_{bn} R_{bun}}{s \cdot E_{д} \cdot \pi \cdot (S^2 - (d+2)^2)}; \qquad (8)$$

However, such a linear relationship between the thickness of the joint and its deformations is not entirely accurate. Thus, [13] describes another calculation hypothesis that is much more consistent with the results of bolt joint tests. It is assumed that the stresses are evenly distributed across the cross-section of the part in the form of a cone starting from the bearing surface of the bolt and nut. The angle of inclination of its sides α is about 22...25 degrees to the vertical. The connection performance diagram according to this hypothesis is shown in Figure 7.

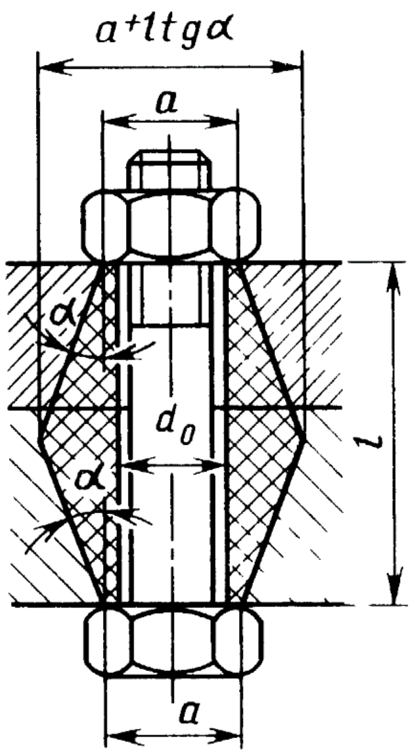

Figure 7. Stress distribution diagram in compressed parts of the assembly, [13]

Nut rotation angle corresponding to the displacement caused by the flexibility of the joint components, with the assumption of a compressed part of the component limited by pressure cones:

$$\varphi_{д2} = \frac{360 \cdot 0{,}7 A_{bn} R_{bun}}{s} \cdot \frac{2}{E_{д} \cdot \pi \cdot d_0 \cdot tg\alpha} * \ln \frac{(a + d_0)(a + l\, tg\alpha - d_0)}{(a - d_0)(a + l\, tg\alpha + d_0)} \qquad (9)$$

The results of the $\varphi_{д2}$ calculation are shown in Figure 8. The final total theoretical nut rotation angle required to achieve the design bolt tension in a shear-resistant connection is shown in Figure 9.

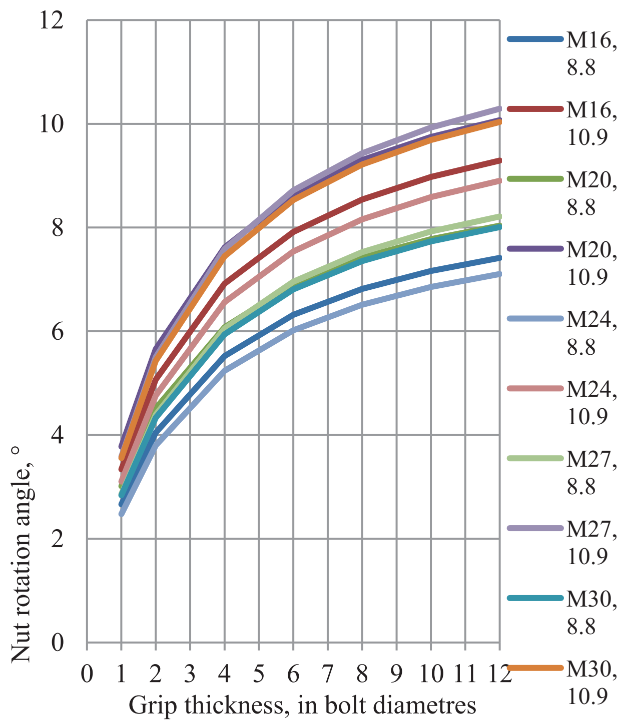

Figure 8. Nut rotation angle corresponding to the displacement caused by the flexibility of the joint components

The relationships between tensile force in the bolt and torque are shown in Figures 10–12, while the relationships between tensile force in the bolt and nut rotation angle are shown in Figures 13–15.

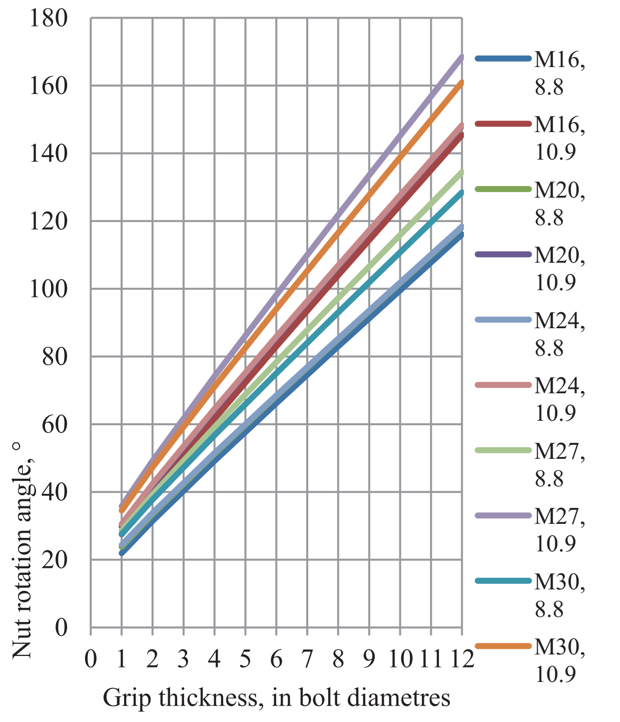

Figure 9. Nut rotation angle required to achieve the design bolt tension

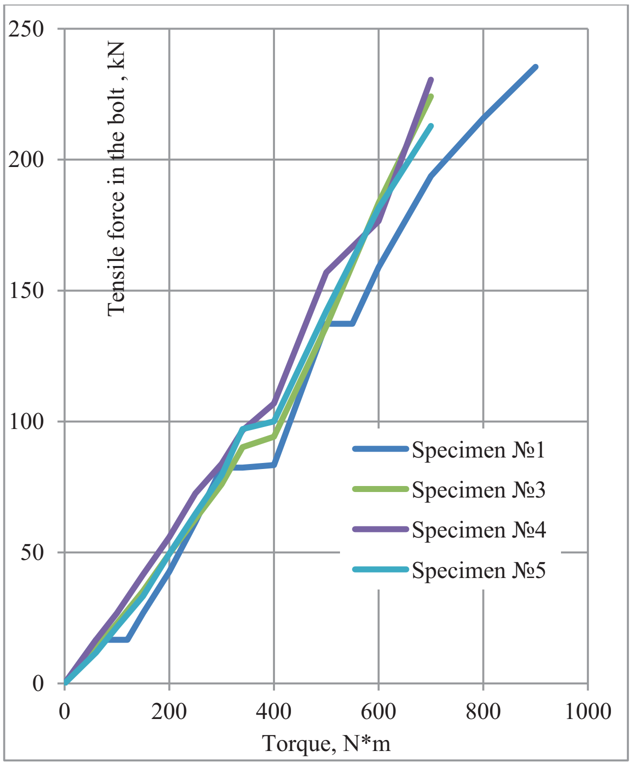

Figure 11. Force vs. torque relationship, M20, 10.9

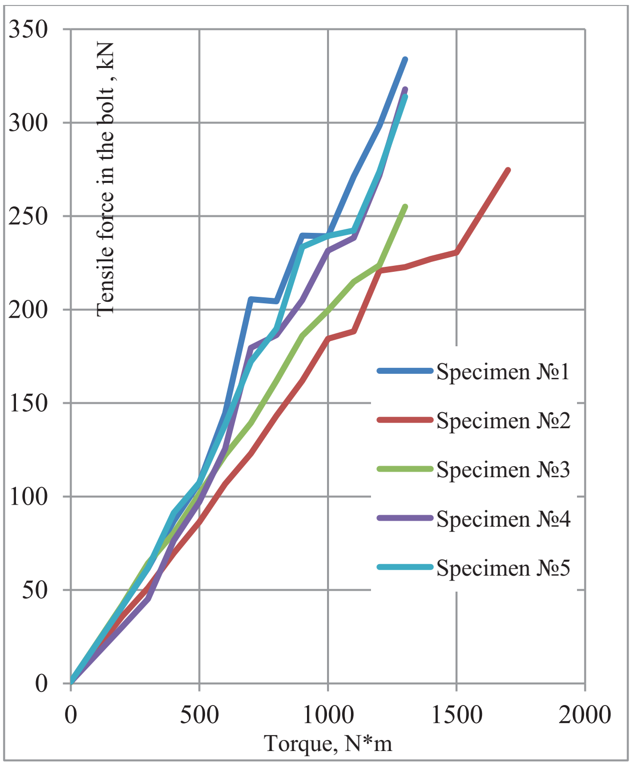

Figure 10. Force vs. torque relationship, M24, 10.9

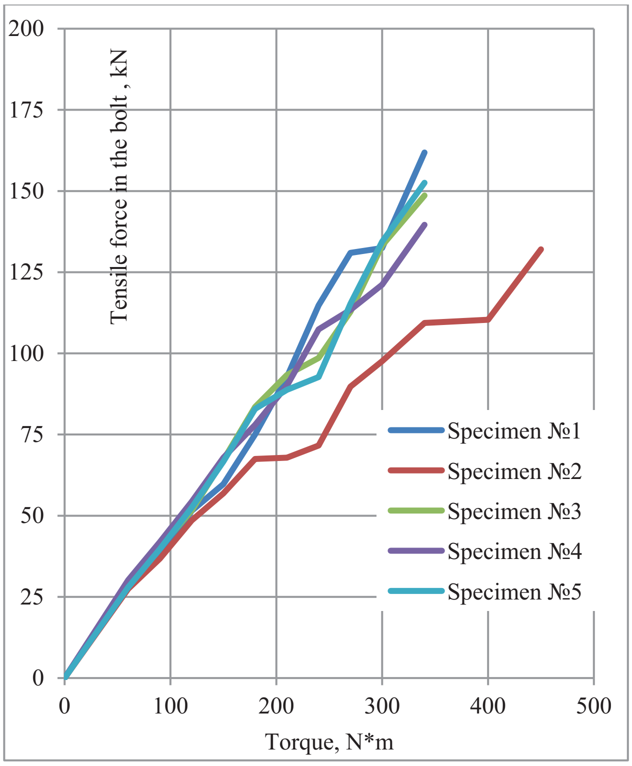

Figure 12. Force vs. torque relationship, M16, 10.9

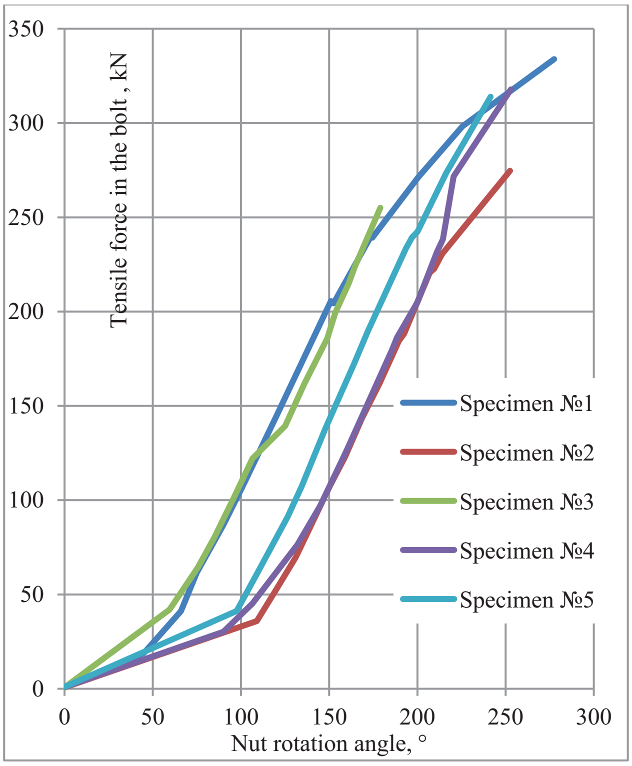

Figure 13. Force vs. nut rotation angle relationship, M24, 10.9

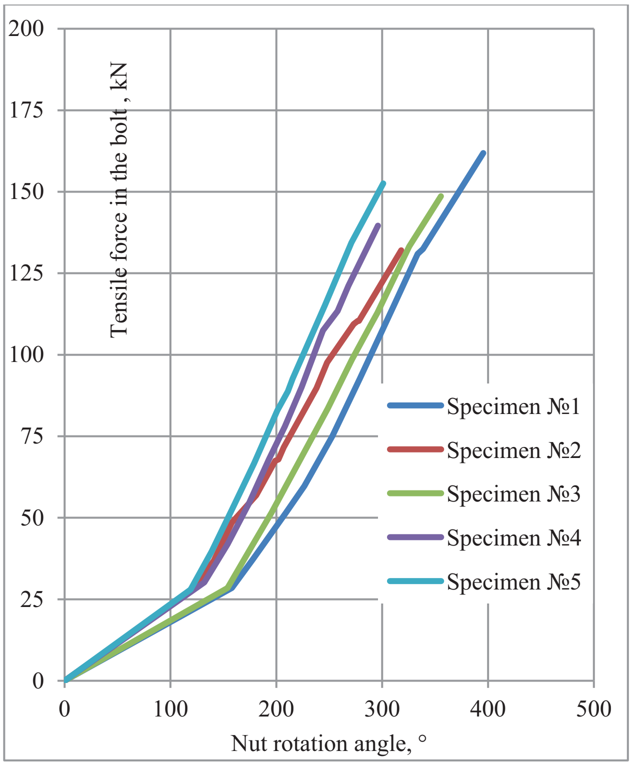

Figure 15. Force vs. nut rotation angle relationship, M16, 10.9

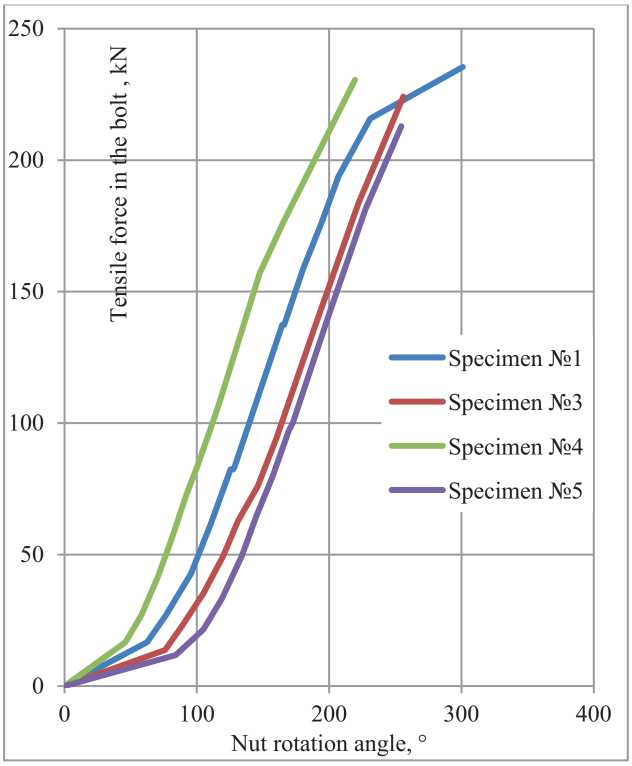

Figure 14. Force vs. nut rotation angle relationship, M20, 10.9

Now we will describe the relationship between the preload force in the bolt and the angle of rotation of the nut. From the point of view of this relationship, the bolt tightening process can be divided into four stages.

The first stage, not shown in the graphs, will be the free rotation of the nut onto the bolt, occurring until the nut comes into contact with the washer. At this stage, no force is generated in the bolt and is equal to zero.

The second stage involves tightening the connection and compressing the washers and other elements. A significant part of the displacement caused by the rotation of the nut is “consumed” not by creating preload in the bolt, but by elastic and plastic deformation of the connection elements, bringing them into contact. The dependence of the force in the bolt on the angle of rotation at this stage is nonlinear.

The third stage is characterized by a linear relationship between the angle of rotation (displacement) and the force in the bolt. It can be assumed that after all the elements of the connection have been brought into contact, its complete “compression”, elastic deformations occur in the connection. Elements such as the thread in the nut and bolt, the plates that make up the connection, the bolt head, and the bolt body itself are deformed. The elastic nature of the deformations occurring in the connection results in a linear relationship between the angle of rotation (displacement) of the nut and the force in the bolt.

The fourth stage is presumably characterized by the onset of plastic deformation in the connection elements. Not all samples reached this state during the experiment; it can be observed in specimen №1 with a diameter of M24. At this stage, the linear dependence of the prestressing force again becomes nonlinear.

We shall compare the test results with the recommendations of various normative documents.

Table 5 shows the rotation angles at which the bolt assemblies achieved the design force, interpreting the process as tightening by nut rotation angle. The rotation angle was determined taking into account the starting reference points defined above (200 N*m, 100 N*m, and 60 N*m, respectively).

Table 6 shows the rotation angles at which bolt assemblies achieved the design force, when interpreting the process as tightening using a combined method. The rotation angle was determined taking into account the reference points defined above (600 N*m, 300 N*m, and 150 N*m, respectively). Determining the angles from these reference points also allows the experimental results to be compared with the values obtained from the calculation.

Table 5. Comparison of experimental results with recommended RCSC and CSA values

Bolt diameter	Specimen	Nut rotation angle	Achieved force, kN	Mean nut rotation angle	RCSC 2020	CSA S16-24
M24	1	134,5	271,25	129,4	180+60	180±30
	2	143,5	274,68			
	3	119,5	255,06			
	4	130,5	271,74			
	5	119,0	273,70			
M20	1	132,0	176,58	123,75		
	3	133,0	183,45			
	4	107,5	176,58			
	5	122,5	181,49			
M16	1	152,5	114,78	141,0		
	2	158,0	110,36			
	3	141,5	112,82			
	4	126,0	113,40			
	5	127,0	115,27			

Table 6. Comparison of experimental results with recommended EN values and values obtained from calculations

Bolt diameter	Specimen	Nut rotation angle	Achieved force, kN	Mean nut rotation angle	EN 1090-2:2018	Calculated nut rotation angle
M24	1	80,5	271,25	77,0	90	74,6
	2	102,5	274,68			
	3	72,5	255,06			
	4	61,0	271,74			
	5	68,5	273,70			
M20	1	69,0	176,58	70,1		84,1
	3	76,0	183,45			
	4	65,0	176,58			
	5	70,5	181,49			
M16	1	152,5	114,78	77,2	120	96,0
	2	158,0	110,36			
	3	141,5	112,82			
	4	126,0	113,40			
	5	127,0	115,27			

CONCLUSION

As shown by foreign experience and domestic and foreign research, the method of controlling bolt tension by nut rotation angle is more accurate than by tightening torque, eliminating the need for time-consuming calibration of torque wrenches and experimental determination of bolt tightening coefficients. It seems relevant to expand the scope of application of this method, which is currently very limited by the guidelines of SP 70.13330.2012.

As a result of developing the proposed calculation model and conducting the experiment, it was possible to obtain the values of the angles of rotation required to achieve the calculated force. The initial hypotheses of the calculation model make its application somewhat limited, but when these hypotheses are satisfied, the values obtained by means of the model correspond to the experimental values.

The nut rotation angles obtained as a result of the experiment are slightly lower than those given in the literature, which may be due to both the large margins included in the standard values and the differences between the experimental setup and the actual operating conditions of bolt assemblies. To study the operation of connection elements at large rotation angles, it is necessary to slightly modify the experimental procedure, bringing the samples to significant plastic deformation. To confirm the obtained data, it is also necessary to conduct a study on a statistically significant sample.

REFERENCES

1. **Andrey Vasilkin, Roman Akhmetzyanov, Georgiy Zubkov and Ilya Vasilkin**. Experimental determination of the tightening coefficient of bolts according to the din standard. E3S Web of Conferences 389, 01080 (2023).
2. **Vasilkin A.A., Zubkov G.V., Prokaev S.A., Vasilkin I.A.** Razmer ploshchadki treniya frikcionnogo boltovogo soedineniya [Friction area of a slip-critical bolt

connection]// Stroitel'stvo: nauka i obrazovanie [Construction: science and education]. 2024. Vol. 14. Issue. 1. p. 4. URL: http://nso-journal.ru. DOI: 10.22227/2305-5502.2024.1.4.

3. **Vasilkin A.A., Zubkov G.V.** Metody kontrolya usiliya natyazheniya boltov sdvigoustojchivyh soedinenij [Methods for controlling the tension force of bolts in slip-critical connections]// Aktual'nye problemy stroitel'noj otrasli i obrazovaniya — 2023: sbornik dokladov IV Nacional'noj nauchnoj konferencii (g. Moskva, 15 dekabrya 2023 g.). Moskva : Izdatel'stvo MISI – MGSU [Current Issues in Construction and Education — 2023: Proceedings of the IV National Scientific Conference (Moscow, December 15, 2023). Moscow: Moscow State University of Civil Engineering Publishing House], 2024.
4. **Василькин А.А., Зубков Г.В.** Deformaciya elementov sdvigoustojchivyh soedinenij pri predvaritel'nom natyazhenii bolta [Deformation of slip-critical connection elements during pretensioning of the bolt].// Aktual'nye problemy stroitel'noj otrasli i obrazovaniya — 2024: sbornik dokladov V Nacional'noj nauchnoj konferencii (g. Moskva, 16 dekabrya 2024 g.). Moskva : Izdatel'stvo MISI – MGSU [Current Issues in Construction and Education — 2024: Proceedings of the V National Scientific Conference (Moscow, December 16, 2023). Moscow: Moscow State University of Civil Engineering Publishing House], 2025.
5. **Martynov G.V., Monastyreva D.E., Makarov A.I., Morina E.A.** Napryazhenno-deformirovannoye sostoyaniye friktsionnykh soyedineniy s lazernoy obrabotkoy kontaktnykh poverkhnostey [Stress-strain state of friction joints with laser treatment of contact surfaces]. Vestnik MGSU [Proceedings of the Moscow State University of Civil Engineering]. 2019. vol. 14. issue. 1. pp. 72–82. DOI: 10.22227/1997-0935.2019.1.72-82. (In Russian)
6. **Kovalenko A.I., Konin D.V., Nakhval′nov P.V., Solov′yev D.V.** Eksperimental′noye issledovaniye koeffitsiyenta treniya friktsionnykh boltovykh soyedineniy [Experimental studyof the friction coefficient of friction bolted joints]. Stroitel′naya mekhanika i raschet sooruzheniy [Construction mechanics and calculation of structures]. 2022. № 4 (303), pp. 61-67. (In Russian)
7. **Vedyakov I.I., Konin D.V., Nakhval′nov P.V.** Eksperimental′noye issledovaniye friktsionnykh boltovykh soyedineniy iz vysokoprochnykh staley [Experimental study of friction bolted joints made of high-strength steels]. Promyshlennoye i grazhdanskoye stroitel′stvo [Industrial and civil construction]. 2022. № 7. pp. 24-33. (In Russian)
8. **Monville J-M:** Optimal tightening process of bolted joints. Int. J. Simul. Multisci. Des. Optim., 2016, 7, A4.
9. **Chaki, Salim & Corneloup, G. & Lillamand, Ivan & Walaszek, Henri.** (2007). Combination of Longitudinal and Transverse Ultrasonic Waves for In Situ Control of the Tightening of Bolts. Journal of Pressure Vessel Technology-transactions of The Asme - J PRESSURE VESSEL TECHNOL. 129. 10.1115/1.2748821.
10. **Jacques Berenbak** Evaluation tightening preloaded bolt assemblies according to EN 1090-2 “Technical requirements for steel structures” for 95% reliability EN 1990 // Delft University of Technology. 2012.
11. **Iosiflevich G.B., Stroganov G.B., Sharlovskij G.B.** Zatyazhka i stoporenie rez'bovyh soedinenij [Tightening and locking threaded connections] 2nd edition, revised and expanded // M.: Mashinostroenie, 1985.
12. **Chesnokov A.S., Knyazhev A.F.** Sdvigoustojchivye soedineniya na vysokoprochnyh boltah [slip-critical

connections using high-strength bolts]// M.: Strojizdat, 1974.
13. **Birger I.A., Iosiflevich G.B.** Rez'bovye i flancevye soedineniya [Threaded and flanged connections]// M.: Mashinostroenie, 1990. – 368 pp.
14. **V.D. Prodan, G.V. Bozhko, A.V. Vasil'ev, M.S.** Fokina Utochnenie koefficienta osevoj podatlivosti rez'bovogo elementa raz"emnogo soedineniya [Specifying the axial ductility coefficient of a threaded element in a detachable connection]// TSTU Bulletin. 2016. Vol 22. № 4. pp. 674-678. DOI: 10.17277/vestnik.2016.04. pp. 674-678.
15. **Kulak G.L.** High Strength Bolting for Canadian Engineers // Canadian Institute Of Steel Construction. 2005.
16. **Bickford, J.H.** (2007). Introduction to the Design and Behavior of Bolted Joints: Non-Gasketed Joints (4th ed.). CRC Press.

СПИСОК ЛИТЕРАТУРЫ

1. **Andrey Vasilkin, Roman Akhmetzyanov, Georgiy Zubkov and Ilya Vasilkin.** Experimental determination of the tightening coefficient of bolts according to the din standard. E3S Web of Conferences 389, 01080 (2023).
2. **Василькин А.А., Зубков Г.В., Прокаев С.А., Василькин И.А.** Размер площадки трения фрикционного болтового соединения // Строительство: наука и образование. 2024. Т. 14. Вып. 1. Ст. 4. URL: http://nso-journal.ru. DOI: 10.22227/2305-5502.2024.1.4.
3. **Василькин А.А., Зубков Г.В.** Методы контроля усилия натяжения болтов сдвигоустойчивых соединений // Актуальные проблемы строительной отрасли и образования — 2023: сборник докладов IV Национальной научной конференции (г. Москва, 15 декабря 2023 г.). Москва : Издательство МИСИ – МГСУ, 2024.
4. **Василькин А.А., Зубков Г.В.** Деформация элементов сдвигоустойчивых соединений при предварительном натяжении болта.// Актуальные проблемы строительной отрасли и образования — 2024: сборник докладов V Национальной научной конференции (г. Москва, 16 декабря 2024 г.). Москва : Издательство МИСИ – МГСУ, 2025.
5. **Мартынов Г.В., Монастырева Д.Е., Макаров А.И., Морина Е.А.** Напряженно-деформированное состояние фрикционных соединений с лазерной обработкой контактных поверхностей // Вестник МГСУ. 2019. Т. 14. Вып. 1. С. 72–82. DOI: 10.22227/1997-0935.2019.1.72-82.
6. **Коваленко А.И., Конин Д.В., Нахвальнов П.В., Соловьев Д.В.** Экспериментальное исследование коэффициента трения фрикционных болтовых соединений // Строительная механика и расчет сооружений. 2022. № 4 (303), С. 61-67.
7. **Ведяков И.И., Конин Д.В., Нахвальнов П.В.** Экспериментальное исследование фрикционных болтовых соединений из высокопрочных сталей // Промышленное и гражданское строительство. 2022. № 7. С. 24-33.
8. **Monville J-M:** Optimal tightening process of bolted joints. Int. J. Simul. Multisci. Des. Optim., 2016, 7, A4.
9. **Chaki, Salim & Corneloup, G. & Lillamand, Ivan & Walaszek, Henri.** (2007). Combination of Longitudinal and Transverse Ultrasonic Waves for In Situ Control of the Tightening of Bolts. Journal of Pressure Vessel Technology-transactions of The Asme - J PRESSURE VESSEL TECHNOL. 129. 10.1115/1.2748821.
10. **Jacques Berenbak** Evaluation tightening preloaded bolt assemblies according to EN 1090-2 “Technical requirements for steel structures” for 95% reliability EN 1990 // Delft University of Technology. 2012.

11. **Иосифлевич Г.Б., Строганов Г.Б., Шарловский Г.Б.** Затяжка и стопорение резьбовых соединений -2-е изд., перераб. и доп. // М.: Машиностроение, 1985.
12. **Чесноков А.С., Княжев А.Ф.** Сдвигоустойчивые соединения на высокопрочных болтах // М.: Стройиздат, 1974.
13. **Биргер И.А., Иосифлевич Г.Б** Резьбовые и фланцевые соединения // М.: Машиностроение, 1990. – 368 с.
14. **В.Д. Продан, Г.В. Божко, А.В. Васильев, М.С. Фокина.** Уточнение коэффициента осевой податливости резьбового элемента разъемного соединения // Вестник ТГТУ. 2016. Том 22. № 4. С. 674-678. DOI: 10.17277/vestnik.2016.04.pp.674-678.
15. **Kulak G.L.** High Strength Bolting for Canadian Engineers // Canadian Institute Of Steel Construction. 2005.
16. **Bickford, J.H.** (2007). Introduction to the Design and Behavior of Bolted Joints: Non-Gasketed Joints (4th ed.). CRC Press.

Andrey A. Vasilkin – Candidate of Technical Sciences, Associate Professor of the Department of Metal and Wooden Structures; National Research "Moscow State University of Civil Engineering" (NRU MGSU), 129337, Moscow, Yaroslavskoe sh., 26; vasilkinaa@mgsu.ru

Georgiy V. Zubkov – graduate student, Industrial and Civil Engineering Institute; National Research "Moscow State University of Civil Engineering" (NRU MGSU), 129337, Moscow, Yaroslavskoe sh., 26; gronar363@gmail.com

Андрей Александрович Василькин – кандидат технических наук, доцент кафедры металлических и деревянных конструкций; Национальный исследовательский «Московский государственный строительный университет» (НИУ МГСУ), 129337, г. Москва, Ярославское ш., 26; vasilkinaa@mgsu.ru

Георгий Владиславович Зубков – аспирант 4 курса Института промышленного и гражданского строительсва Национальный исследовательский Московский государственный строительный университет (НИУ МГСУ), 129337, г. Москва, Ярославское шоссе, 26, адрес электронной почты: gronar363@gmail.com