Experimental determination of the tightening coefficient of bolts according to the din standard

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Abstract. The use of slip-critical connections is very common in the design of critical steel structures and is seen as an effective way to transfer the force in conditions of dynamic loading. The limit state of the connection occurs when the calculated shear stress is reached, which depends on the friction coefficient of the contact planes and the value of the clamping force, equal to the bolt tension stress. In order to ensure the necessary bolt tensioning force, it is necessary to know the bolt tightening coefficient, because according to the current understanding of the slip-critical connection performance, the designed functioning of the bolt connection is ensured when the bolt tensioning force arising at the necessary torque value is achieved. Otherwise, the actual work of the connection will be different from the calculated, because only a given tension force provides the estimated bearing capacity of the bolted connection with friction planes. This article focuses on tensile testing of a bolt and determining the tightening factor of a bolt made of high-strength10.9 M14 steel. The tightening factor is determined with strain gauges by measuring the relative strain of the bolt when the nut is tightened. This method requires specialized equipment and a test bench and can be used in the study of bolt performance in the absence of a certificate or the need to verify or clarify the available data. The results show that the proposed method can provide a stable determination of the coefficient value. The examined bolts were made according to the German standard DIN931, strength 10.9 size M14x220, nuts according to the German standard DIN934, strength 10 size M14. An Instron 1000HDX tensile testing machine was used to plot the performance of the bolt steel. Nut tension control was determined with the use of NOGRAU NTW24-034R torque wrench, and bolt elongation control with FLA 5-11 strain gauges and National Instruments data acquisition system. On the basis of the conducted research, a method for determining the tightening factor of high-strength bolts has been tested and proposed. The proposed method of determining the tightening factor of a high-strength bolt can be used in research work and allows to determine the coefficient in the absence of an appropriate certificate or the need to clarify (verify) the stated value of the coefficient.

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1 Introduction

It is known that the bearing capacity of the slip-critical connections is provided by the friction forces between the connecting surfaces [1]. To increase the bonding force between the connected plates, a bolt is tightened in such a way, that stress is equal to the bearing capacity of the bolt. The first domestic studies of slip-critical connections were carried out in the USSR in 1957 [2]. Bolt made of 40X steel was tightened to a force close to the bearing capacity of the bolt (20t for a M22 bolt). Then coefficient of friction was determined, equal to the ratio of the shear stress to the bolt tension stress. After numerous tests and statistical processing, the friction coefficients was normalized and used to determine the bearing capacity of a slip-critical connection with one friction plane and, accordingly, the bolt connection is further calculated by determining the required number of bolts.

Nowadays, the research on the actual performance of a bolt is mainly aimed at identifying the influence of various factors on the load-bearing capacity of the connection.

In [3], for example, the authors determined the load at which the bearing capacity of the connection is provided by friction forces and compared it with the calculated one.

In [4] it was found that when the ultimate strength of a bolt changes, there is a proportional change in the tightening coefficient. It was concluded that based on the stochastic evaluation of this correlation, it is possible to reduce the number of bolts during mechanical tests in the case of testing bolts of different strengths, because the probabilistic dependence of the tightening coefficient and the bearing capacity of the bolt was established.

In [5] the effect of corrosion on the bearing capacity was evaluated, and the effects of temperature [6], repeated loading [7], seismic vibrations [8], the method of treatment of the surfaces being joined [9-11] were also investigated.

A number of authors have tested the actual performance of friction joints on physical [12-16], and mathematical models [17].

There are few studies of the tightening coefficient of a bolt, only the authors of [18] determine the torsional coefficient for different types of lubrication.

Since the bolt tensioning force depends on the bearing capacity of the bolt, which in turn depends on the diameter, the required bolt tensioning force for each diameter is given in the standards [19]. The current standards for M22 bolt indicate a tensioning force of 22 t, which is comparable to the force at which the high-strength bolts were tested in 1957. It is obvious that at lower tensioning forces of the bolt the friction coefficient between the connected surfaces will have a different value and the calculation of the joint without new numerical data is impossible.

Tensile stress occurs in the bolt rod due to the tightening of the nut, which must be controlled to ensure the specified tightening force. The following methods of bolt tension control are traditionally used - by the angle of rotation of the wrench, by the torque of tightening, by the amount of bolt extension [19,20].

Currently, the only way to control the bolt tension, allowed by domestic normative documents for use, is torque control [21]. Although the standard document SP 70.1336.2012 " Bearing and enveloping structures" allows you to control the bolts tension by the angle of rotation of the nut for the bolts M24 of strength class 10.9. Given the widespread use of torque wrenches, this method can be used in the installation process, but it is necessary to daily calibrate the key, which is an additional technological operation, which increases labor intensity.

The torque that must be applied to tension the bolt is determined by the expression:

$$Mt = k*db*Pbh \qquad (1)$$

Where M_t is the torque in N*m,
P_{bh} is tensile force, kN - specified in the standards,
k is tightening coefficient of the bolt,
d is the bolt diameter, mm.

The value of the required torque is also given in the normative literature [19]. This value is important because it determines whether the slip-critical connection will work according to theory. In addition, the torque is the only parameter that can be monitored in the installation conditions without additional equipment and highly qualified personnel.

As follows from formula (1), the torque is directly proportional to the bolt tightening factor k. The accuracy and correctness of its value determines the accuracy of the tensile force calculation and, ultimately, the load-carrying capacity of the connection.

For each batch of high-strength bolts, the manufacturer indicates the bolt tightening coefficient - k. Bolts must have a tightening coefficient of not more than 0.20 and not less than 0.14. The coefficient is determined by the method in accordance with GOST 22356-77, with the help of a dynamometer, by which the bolt tension force is determined [20].

In this paper, an alternative method for determining the bolt tightening coefficient using strain gauges is proposed and tested.

2 Materials and methods

In the first phase of the study, the tensile strength of the bolts was determined. It was compared with the standard strength specified in the certificate to determine the bearing capacity reserve and the possibility of exceeding the standard torque.

To determine the tightening coefficient k, high-strength M14 bolts of strength class 10.9, made of steel according to German standard DIN 931, as well as high-strength washers and high-strength nuts made of steel according to German standard DIN 934 were used. According to the requirements of STP 006-97, GOST 1759.4-87 and GOST R 52643-2006 five bolts were used for the study. The study was carried out in the laboratory of tests of building materials, products and structures of the Moscow State University of Civil Engineering.

The tested bolts were placed in the Instron 1000HDX tensile testing machine (Fig. 1) and driven to failure. Afterwards, diagrams of the material performance of the bolt were plotted. In order to avoid thread shearing under tension, three nuts were screwed onto each bolt. As expected under uniaxial tension, bolt failure occurred along the threaded portion of the bolt (Fig. 1).

Determining the actual load capacity of the bolt is necessary to calculate the maximum torque that can be applied when tightening the nut. In the second stage of the study, the bolt tightening coefficient was determined.

Each bolt was prepared according to the requirements of the normative document [22] and a 5 mm strain gauge (FLA-5-11) was glued on it.

The high-strength bolt was installed in the tensile testing machine, with one high-strength washer each under the head and nut, and after installing the bolt on the frame, (Fig. 2.) the contact from the wires was connected to the National Instruments data acquisition system, which took data on the relative elongation of the bolt. The bolt was tensioned by tightening the nut with a calibrated torque wrench (max Mcr = 360 N*m) with possible torque increments of 2 N*m. Bolt tightening was carried out with constant speed, without jerking, a torque step of 20 N*m was chosen.

Fig. 1. Left: Installation of a high-strength bolt in a testing machine. Right: bolt failure along the threaded portion of the bolt.

During the first bolt test, the washer was pierced by the nut, presumably due to a large gap between the diameter of the hole and the diameter of the bolt, which was 5 mm (Fig.2). Therefore, the bolt was tested in a set of plates with a cutout to ensure the integrity of the strain gauges (Fig.5).

Fig. 2. Left: Testing the bolt on the stand. Right: piercing of the washer.

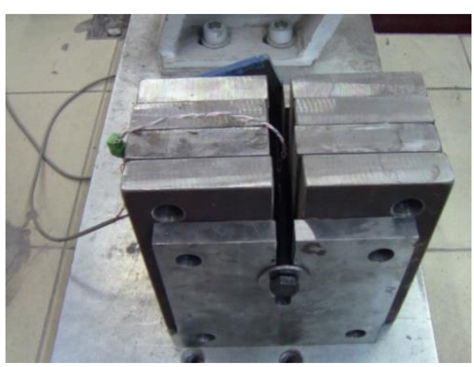

Fig. 3. Testing the bolt in the plate package.

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3 Results

As a result of the experiment on axial tension of the bolts, a diagram of the bolts' steel performance was plotted by the analytical module of the testing complex (Fig.4). Table 1 shows the tensile strength of the tested bolts, the corresponding relative elongation and the nominal load-carrying capacity of the bolt according to the certificate.

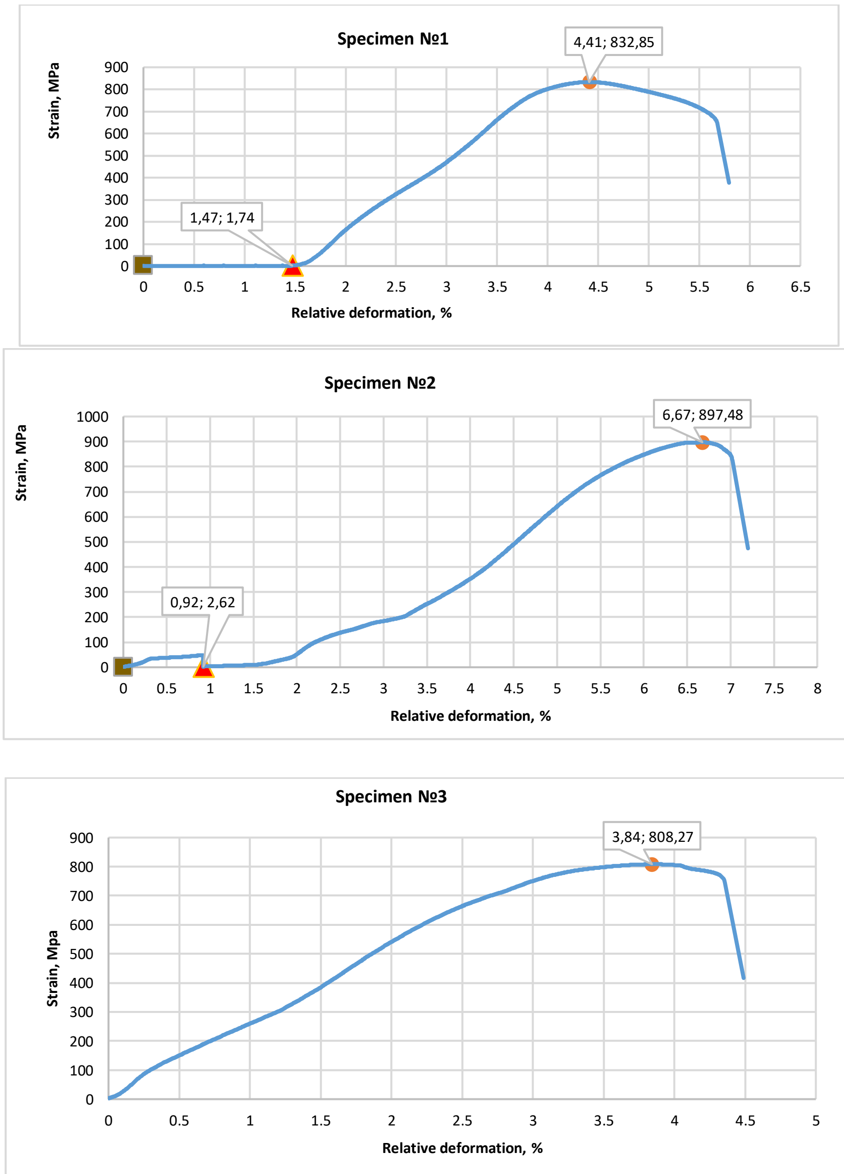

Fig. 4. Diagrams of the steel bolts performance.

As a result of the bolt test, the bench outputs data on bolt elongation in mm and stress in MPa. The relative strain is determined analytically by the expression:

$$E = \Delta l / l * 100\% \quad (2)$$

where Δl is the elongation in mm given by the test bench, and l is the length of the bolt from the head to the fracture point.

In addition, it is necessary to consider that at the beginning of the tensile test the bolt is moving (crimping/seating) in the clamps, as demonstrated by the horizontal section in the graphs of specimens 1 and 2.

Table 1. Values of actual and nominal strength characteristics of the bolt.

Model	**Bolt strength limit, MPa**	**The corresponding value of the relative deformation, ε, %**	**Bolt strength according to the certificate, MPa**
1	832.9	~ 3.0	780
2	897.5	~ 5.7	780
3	808.3	~ 3.8	780

In the second part of the experiment, when determining the torque coefficient, almost all samples reach a tensile peak at a torque of 200 N*m, and when reaching 220 N*m, thread shearing occurs.

After the data were processed, diagrams of the M – ε function were plotted for specimens 1-5 (Fig. 5).

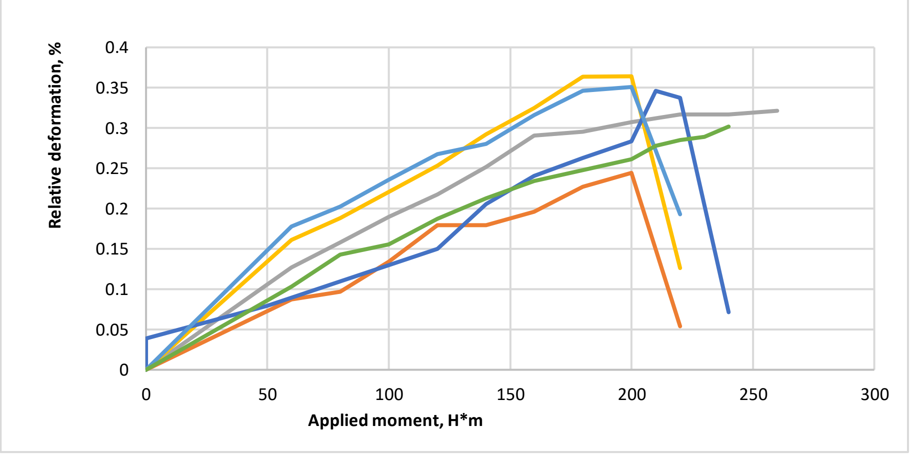

Fig. 5. M – ε function.

From the analysis of the graph, we can conclude that the bolt works in the elastic stage and reaching the limit state is achieved by the thread shearing, which means that the bolt material does not reach the plastic stage of performance.

Therefore, we can use Hooke's law to determine the normal stresses in the bolt:

$$\sigma = E^* \varepsilon \qquad (3)$$

Next, we determine the axial bolt tension force P and calculate the bolt tightening coefficient using the following equation:

$$K = Mt/(P^*d) \qquad (4)$$

Although the standards determine the tightening coefficient k for a single torque value, a graph of the tightening coefficient versus torque was plotted, showing that the tightening coefficient value is close to the approximating line and increases as a function of the tightening force (Fig. 6).

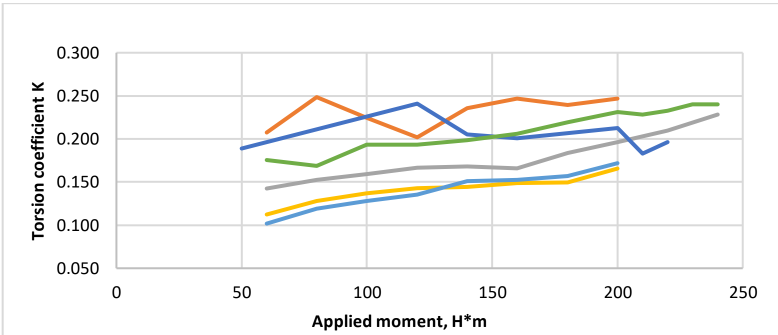

Fig. 6. M – k function.

It follows from the data presented that with different torque values, the tightening coefficient also has different values. This means that if, during installation, the goal is to tighten the bolt to a slightly lower torque than specified in the standards, not only should the torque be reduced, but a new value for the tightening factor should also be considered, which will differ from the value in the bolt certificate.

Appendix D of GOST 32484.3-2013 provides recommended bolt tensioning forces to determine the tightening coefficient. The tightening coefficient value is determined at the moment when the standard bolt tension force is reached, at which the value of the torque is recorded. For a bolt M14, strength class 10.9, the standard tension force is 80.5 kN and the tension created is 700 N/mm2. Let's determine the tightening coefficient for these values.

Specimen 1 did not reach the standard tensioning force, because it began to bend the power frame and pierced the washer because of the significant difference in the diameters of the hole and the bolt.

For specimen 2, there are two adjacent values at a torque of 160 and 180 N*m, which shows that the required values are in between the readings taken, but still the torque factor has the same value of k = 0.149.

For statistical processing of the obtained results, we determine the coefficient of variation of the tightening factor, which should not be more than 0.10. So the value of the tightening factor k = 0.240 for bolt No. 5 should not be taken into account.

So, the individual values of the torque coefficient are given in Table 2. The average value of tightening coefficient of the tested batch of bolts km = 0,163 is within the limits of GOST 32484.3-2013: 0,11 - 0,20, which indicates the possibility of using the presented method of determining the tightening coefficient of the high-strength bolt.

Table 2. Values of the tightening coefficient.

Bolt Number	**Applied moment, H*m**	**Relative deformation, %**	**Strain, kN/cm^2**	**Tensile strength, kN**	**Torsion coefficient K**
Required values according to GOST			*70*	*80.5*	*0.11-0.20*
2	160	0.32473	66.894	76.929	0.149
	180	0.36365	74.911	86.149	**0.149**
3	210	0.34604	71.284	81.977	**0.183**

4	180	0.346	71.259	81.948	**0.157**
5	270	0.33976	69.990	80.489	0.240
Average value of the tightening coefficient					**0.163**
Standard deviation					0.01777
Coefficient of variation of the tightening coefficient					0.10905

4 Conclusion

In the conducted researches conclusions about bolts strength estimation are made, methods and techniques which allow to determine bolts strength and tightening factor are shown. Experimental data have been obtained, which make it possible to estimate the force at which the required tightening coefficient will be achieved, and the dependence of the tightening coefficient on the tightening moment has been determined.

Thus, the article proposes and describes a method for determining the tightening factor of a high-strength bolt. At the same time, additional experimental studies confirming the obtained data are required to evaluate this method and its application with bolts of other diameters and strengths.

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