Experimental studies of flange connections with gaps

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Abstract. Particular interest for solving engineering problems is the question of the actual operation of the building frame as a whole, taking into account the peculiarities of the operation of joint solutions connecting the main elements. It is proposed to investigate the effect of initial gaps in flanged "beam-column" type connections on the strength and deformation characteristics of the joint solution. Particular attention is paid to the work of high-strength bolts with preload in the "tension with bending" mode of operation. In this article, the configuration of the experimental model is proposed, a method is chosen for relieving stresses in bolts through three points, which makes it possible to keeping in view stresses not only along the axis, but also in the plane of the cross-section of the bolt. Materials and methods: pre-tests and recommendations for full-scale experimental studies of a frame fragment based on the results of a numerical calculation of an equivalent model. Results: tensile testing of a bolted connection to determine the mechanical properties of bolts, taking into account the weakened section, recommendations for making changes to the full-size experimental model of the assembly, being mindful of the results of this study. Conclusions: substantiation of the methodology for conducting the experiment on the subject of the study.
Key words: beam-to-column end plate joint, friction connection with initial gaps

1 Introduction

The design of steel frames requires the designer to solve such issues of strength, rigidity, ease of assembly, steel consumption and labor intensity of the structure. To find the most rational solutions, it is necessary given that the actual operation of the elements and nodes of the frame.

Installation of steel structures is carried out mainly on bolts of various strength classes. The flanged frame assembly "beam-column" is widely used in the frames of multi-storey buildings. Columns and beams are often used in the frame and are made of I-beams rolled or welded I-beams. To simplify the design, the column may not have transverse stiffeners in the node.

The connection of the beam with the column can be performed using standard nodes [1-3]. Such nodes are well studied, but have a complex design, contain redundant elements.

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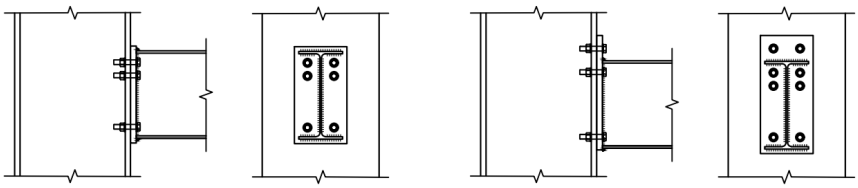
This is due to the preference given to the use of nodes that are as close as possible to a rigid connection by the nature of the work. Research is also underway to determine the nature of the operation of flange assemblies without additional reinforcement elements in various configurations [4-9]. On fig.1 two types of nodes are presented, the simplest in terms of design.



a) b)

Fig. 1. Non-reinforcement end-plate joints.
a) type 1 - node is a connection with a flange within the height of the beam (flush end-plate joint);
b) type 2 - node is a connection with an extended flange (extended end-plate joint).

A number of scientific publications present the results of studies of flange assemblies taking into account their stiffness parameters [10-20]. To determine the stiffness characteristics, the results of calculations of finite element models and experimental data are used. The issue of initial imperfections is discussed to a lesser extent, more preference is given to the study of the work of compounds under different types of dynamic, thermal and special loads. The question of the operation of various steels, their advantages and disadvantages in specific operating conditions is also investigated.

It should be noted that the current methodology for considering the stiffness characteristics of the joint, set out in the Eurocode, is very time-consuming to apply in practice. The advantages of the Eurocode methodology include the possibility of being mindful of the contribution of each individual structural component to the rigidity of the joint.

Russian and foreign studies show that minimal initial imperfections, such as welding deformations of the flange, do not negatively affect the strength properties of the joint, while reducing the initial stiffness of the joint. For the design of reliable flange assemblies, it is necessary to determine what the value of the initial gaps in the flanges is permissible when designing connections and what contribution the gaps make to the operation of the node.

The analysis of the rolling profiles used for the manufacture of columns showed that the deviation of the shelf of the rolling profile of the column from parallelism has the greatest influence on the formation of the initial gaps between the flange of the beam and the shelf of the column. According to GOST R 57837-2017, with a profile height from 120 to 290 mm, the difference in the shelf plane along its length should not exceed 3 mm, with a height greater than 290 mm - 4 mm. In the current study, it is proposed to consider the non-parallelism of the column and beam flanges with the opening of the gap in the horizontal plane of the joint. The article presents the test results of the first type of assembly at different clearance values on one side of the flange.

2 Methods

In order to determine the effect of the initial gap between the flange and the column shelf on the stress-strain state of the joint, it is proposed to test experimental flange assemblies "beam-column". At the second stage, considering the successful experience of using the finite element method [9], it is assumed to conduct a numerical experiment.

Keeping in view the restrictions on the permissible height during the experiment, the column is made with a length of 1500 mm from a rolling I-beam 40K1, which has a high torsional rigidity. The experimental beam is made of a rolled I-beam 25B1.

Bolts with a diameter of 16 mm, strength class 8.8 are used to attach the beam to the column. The use of bolts of strength class 8.8 in flange assemblies is permissible in structures of any responsibility classes. The parameters of the bolts ensured the operation of the joint in the absence of plastic deformations in the joined elements.

In order to evenly distribute the load from the pre-tension of the bolts between the tightened elements, the thickness of the column shelf and the flange are assumed to be approximately the same thickness. The 40K1 I-beam column shelf has a thickness of 18 mm, the flange thickness is 20 mm.

To determine the stress-strain state of the bolts in the flange connection, a connecting part was made from a stud of strength class 8.8 with a diameter of 16 mm, in which grooves were cut for fixing three load cells with a base of 3 mm and a resistance of 120 ohms. Three sensors make it possible to obtain not only data on the longitudinal force in the bolt, but also on the bending moment in it. The stud is fastened with nuts of class 8. A lock nut is used to fix the position of the nuts. The general view of the hairpin is shown in Fig.2.

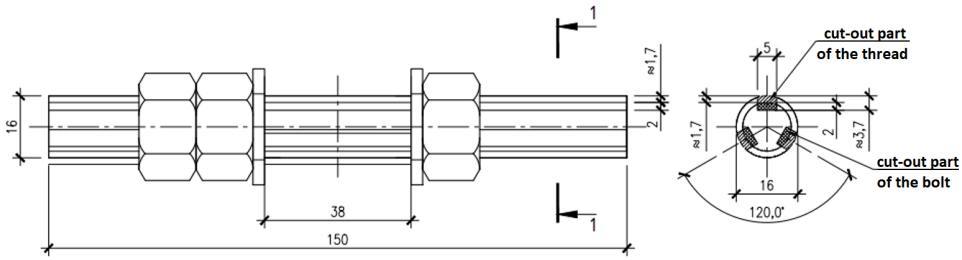


Fig.2. Bolt specimen

Before the experimental studies of the nodes, the tension tests of the stud were carried out to determine the mechanical characteristics of the stud steel. In addition, tests of studs with slots and glued strain gauges were carried out, which made it possible to clarify the size of the slots and the operability of the proposed method for measuring stresses in the stud. The cross-sectional area of the stud, considering the slots, was 1.05 sm^2. Figure 3 shows a stud with slots and glued load cells during the test.

Fig.3. Bolt specimen test

The results of the stud tests were used to refine its design. After testing the studs and clarifying the design of the studs, an experimental installation was assembled. On fig. 4 shows an experimental setup with a node of the first of the considered types prepared for testing.

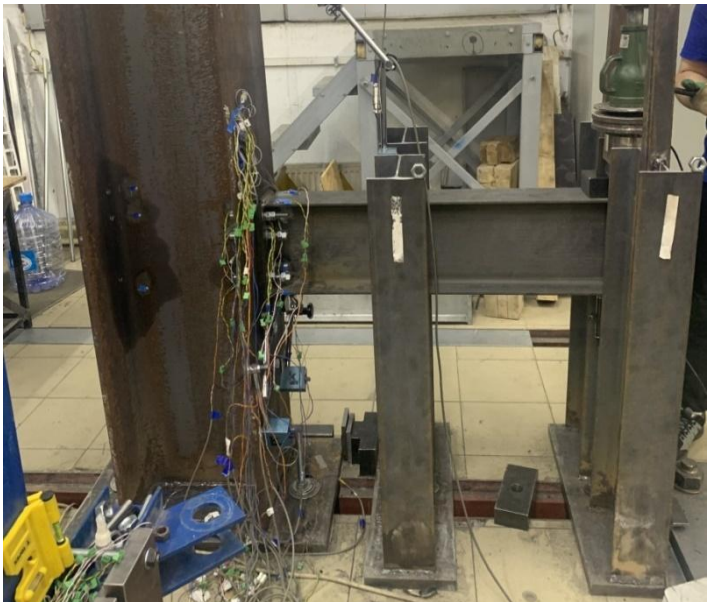


Fig. 4. Experimental specimen of end plate joint

When assembling the installation, procedures were worked out to form the required uneven gap while ensuring reliable fixation of the column and beam. The operability of the design has been checked, the test program has been clarified. The trial loading of the type 1 node confirmed the design assumptions adopted during the design of the installation.

During assembly, such a position of the beam and column was achieved so that when tightening the bolts, taking into account the deformation of the flange, the necessary gaps were provided on one side of the flange. To form a gap, the column was rotated relative to the longitudinal axis at the required angle, after which it was fixed with anchor bolts to the power floor. The gaps were measured by a set of engineering probes with 0.05-1 mm plates. When assembling the installation, the beam is pre-fixed relative to the column, and then

fixed with studs, which were tightened with the control of relative deformations in the sensors. When tightening the studs, the force in them was controlled so as not to exceed the calculated value equal to:

$$P_b = 0,6 \cdot R_{bt} A_{bn} = 0,6 \cdot 451\ N/mm^2 \cdot 105\ sm^2 = 28\ kN \tag{1}$$

3 Results

When conducting tests to determine the mechanical properties of the stud sample, the following conditional yield strength, time resistance, modulus of elasticity were obtained. In Table.1 presents the results of the stud tear test.

Table 1. Mechanical Properties of Bolt Steel.

Fact cross-sectional area bolt specimen, mm²	Yield tensile stress force, kN	Yield strength, N/mm²	Normalized design resistance of 8.8 class bolts, N/mm²	Ultimate tensile stress force, kN	Ultimate tensile strength of bolt specimen, kN/mm²	Normalized normative resistance of 8.8 class bolts, N/mm²
104,7	59,64	569,5	451	93,39	891,0	830

Figure 5 shows the "strain-load" relationship obtained when testing a hairpin for tension. The flow limit and time resistance are marked on the diagram.

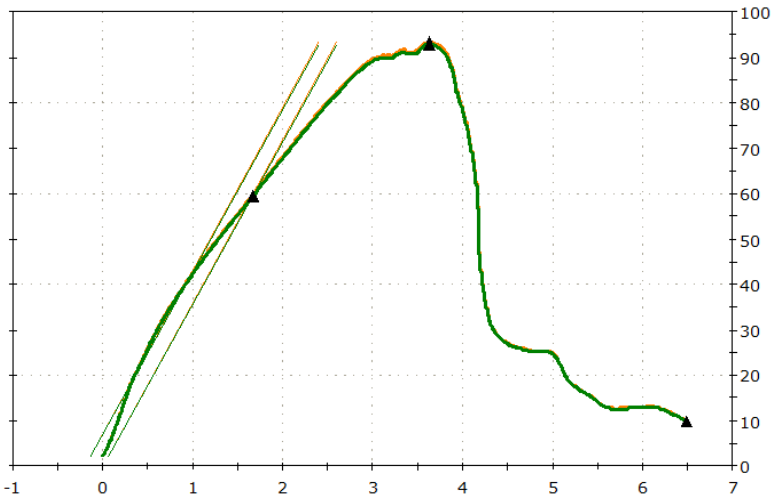


Fig. 5. Srain-load diagram

When determining the mechanical characteristics of the steel studs, compliance of the steel studs with regulatory requirements was established. The elastic modulus of the stud material to the yield point was $2,03 \cdot 10^5$ MPa.

In Table.2 presents the results of testing a stud with slits for tension. Figure 6 shows the dependence of the voltage in the stud with slots on the load according to the readings of strain gauges and the theoretical value of the stresses.

Table 2. Load and voltage in sensors.

	Yield tensile stress force 59,64 kN	**Ultimate tensile stress force 93,39 кН**
Sensor №1		
Strain	0,002835	0,004243
Stress, MPa	575,5	861,3
Sensor №2		
Strain	0,001998	0,003810
Stress, MPa	405,6	773,4
Sensor №3		
Strain	0,002788	0,004217
Stress, MPa	566,0	856,1
Average value by sensors №1 и №3		
Strain	0,002812	0,004230
Stress, MPa	570,8	858,7

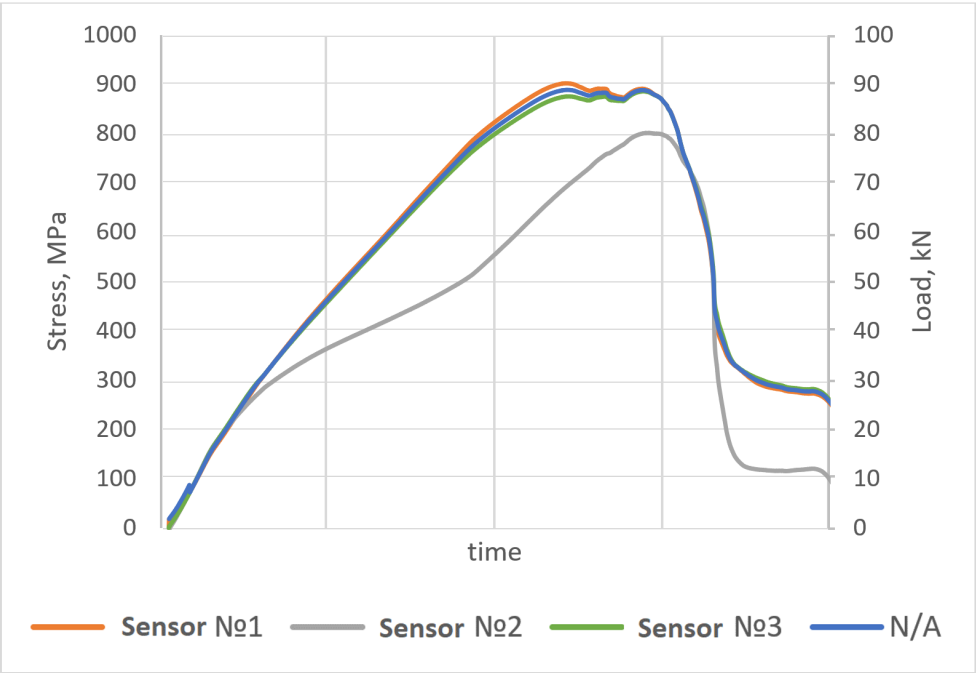


Fig. 6. The diagram of theoretical and fact tension in strain gages

Testing of a sample of a stud with slots allowed us to establish the nature of the destruction. As a result of loading of the experimental sample, the joint lost its bearing capacity according to the thread material of the nut of class 8 with the removal of the key 5.4 washer (Fig. 7). The material of the stud, considering the section weakened by the grooves, corresponds to the normalized values of the design resistance of bolts of class 8.8 and was not destroyed during the test. The readings of sensors No. 1 and No. 3 coincide with the theoretical values. For sensor No. 2, there is a deviation from the theoretical values.

Fig.7. Destroyed bolt joint

The stud tests confirmed the operability of the sensors in the slots of the studs. The sensor readings adequately reflect the force acting in the stud. Preliminary gluing and desoldering of strain gauges, assembly of the threaded connection and fixing of sensor wires, testing of the stud allowed us to establish that it is permissible to reduce the depth of the groove in the stud to accommodate sensors up to 3.4 mm. Since the destruction occurred according to the material of the nut thread, in further tests of the flange assemblies, lock nuts are used on each side of the joint. The stress values in the bolts were taken according to the average deformations of 3 sensors.

The test results were obtained with three variants of the gap formed in the area of bolts number 4-6: 1 test a gap of 1 mm; 2 test a gap of 1.8 mm; 3 test a gap of 4.7 mm.

In the first test, the bolts were tightened by a force of 24-28 kN (Table 3).

The difference in tension is due to the redistribution of the tension force between the bolts during their successive tightening and force adjustment.

Table 3. Pre-tension of bolts, the first test

№ bolt	1	2	3	4	5	6
Tension force, kN	27.7	28.5	27.3	23.9	25.7	25.6

The maximum concentrated force on the beam console at a distance of 900 mm from the flange was 35 kN. The maximum load was set upon the fact that one of the bolts reached a voltage of about 400 MPa with a normalized breaking value for bolts of Class 8.8 equal to 451 MPa. Unloading was carried out without exposure.

Fig. 8 shows the change in the stresses in the bolts depending on the load. The red color shows the load change, the blue color shows the voltage in the bolts.

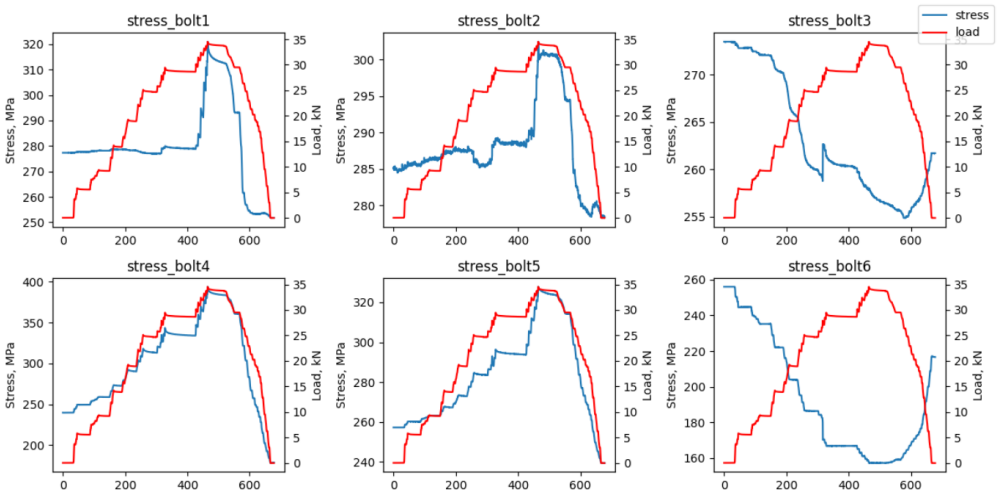


Fig. 8. The tension in the bolts, the first test

The bolts of the upper rows in the zone of tight connection of the flanges (No. 1,2) retain stresses at the level of the pre-tightening value up to a certain load value (about 28 kN), after which the stresses in them begin to grow rapidly. The forces in bolts number 4 and 5 located in the gap zone increase and increase immediately and in proportion to the increase in load on the beam. The immutability of the forces in bolts 1 and 2 at the initial stage of loading is due to the fact that the contact of the flange with the column shelf in the area of tight abutment is broken and the flange after reaching a force of 28 kN in the area of bolts 1 and 2 does not come into contact with the shelf, all compressive stresses in the shelf and flange in the direction of thickness are removed., and bolts 1 and 2 are additionally stretched when the load increases. The forces in bolts number 1 and 2 then reach values corresponding to the forces in bolts 4 and 5 initially operating in the absence of contact between the flange and the shelf. After unloading, the stresses in the bolts of the stretched zone are reduced by 3-30%.

The bottom row of bolts is located in the compressed area of the node. With increasing load, the tensile stresses in them, as expected, fall with increasing load. The drop in pre–tension from the tight-fitting side (bolt No. 3) was 18.6 MPa, and from the gap side (bolt No. 6) - 98.9 MPa. After unloading, the stress reduction in the bolts of the compressed zone was from 8 to 14%.

On fig. 9 shows the dependences of stresses in the flange when the load changes.

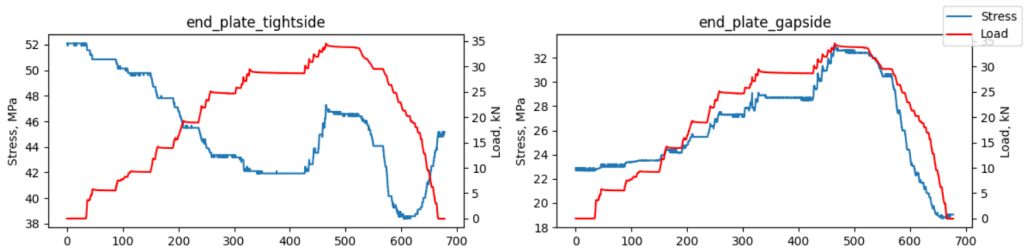


Fig. 9. The tension in the end plate, the first test)

The first graph shows the operation of the sensors up to the tight fit side of the flange to the shelf, the second – from the gap side. At the initial moment of time, the voltage from tightening the bolts at the point of the first group of sensors was 52.1 MPa, in the second – 22.7 MPa. With an increase in the load, there is a decrease in the voltage in the installation zone of the first pair of sensors to 42 MPa at a load of 28 kN, then the voltage increases to 46 MPa when the maximum load is reached. An additional increase in stresses in the compressed zone of the flange occurs at the same load as the increase in stresses in the bolts of this zone. In the gap zone, the stresses in the flange increase as the load increases over the entire loading range.

The second and third tests of the first type of assembly confirmed the operability of flange assemblies with excess gaps. Qualitative results coinciding with the first test were obtained. The growth of stresses in the bolts by increasing the gap was revealed. It was found that with an increase in the gap from 1 to 4.7 mm, the stresses in the bolts increase at least 1.6 times.

4 Discussion and conclusions

The analysis of the features of the tasks being solved to account for the effect of gaps on the operation of flange connections, the results of numerical calculations of flange assemblies and data from previous studies allowed us to develop the design of experimental samples and installations for conducting multivariate tests of two types of nodes with varying the gap between the flange and the column shelf. During the preliminary tests of the stud of class 8.8, the mechanical characteristics of the stud steel were determined. The feasibility of determining the stresses in the stud using strain gauges placed in the slots and the reliability of the data obtained are confirmed. According to the test results, the dimensions of the slots were adjusted and it was decided to use twice the number of nuts or increase the class of nuts to 10 for reliable fixation of the stud.

• A model of an experimental sample has been developed, a method for forming initial gaps between the flange and the column shelf has been proposed.

• The design of a stud with slots is proposed, which ensures the placement of load cells in them and the output of wires without going beyond the dimensions of the bolt along the external thread, which ensures the safety of sensors and wires during the experiment.

• The dimensions of the slots and the parameters of the nuts were clarified based on the results of preliminary tests that confirmed the reliability of the data received from the sensors. The stud sample, considering the weakening of the cross section for the placement of load cells, corresponds to the normalized strength characteristics required for bolts of class 8.8.

• The theoretical assumptions about the nature of the bolts in a given configuration have been confirmed – the upper rows work with an increase in tensile forces, while in the lower row the stresses drop. It is recorded that in the stretched zone of the node, with full contact of the flange and the shelf, the column stresses in the bolts maintain the initial level to a certain load value, after which they rapidly increase with increasing load. In the stretched zone of the node, in the presence of a gap, the tensile stresses increase in accordance with the increase in load.

• The nature of the work of the bolts and the flange plate of the beam in the node in the presence of gaps of various sizes is revealed. It is established that an increase in the gap leads to an increase in stresses in the most loaded bolts by at least 1.6 times and can lead to a change in the nature of the operation of neighboring bolts, the increase in stresses in the flange with large gaps occurs faster.

• The operability of the flange connections has been established at gaps exceeding the permissible

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