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RESEARCH ON THE PERFORMANCE OF STEEL JOINT CONNECTORS IN CROSS-BEAM CONSTRUCTIONS MADE OF GLULA

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Abstract. Cross-beam systems involve the use of beams that are connected to each other at a certain angle, which allows for effective load bearing and increased structural rigidity. Connections using bolted joints with metal connectors are particularly relevant in cases where it is necessary to increase resistance to dynamic and static loads. The paper presents the results of a study of the stress-strain state of a joint with an original connector of a cross-beam slab made of glued wood under the influence of a static load. Two samples of the joint connection were manufactured for testing. The first is a prototype of a cross-beam slab joint, supported at the corners, with variable cross-sections of elements, and the second is a control sample with constant cross-sections of elements along their entire length. A distinctive feature of the connector for joining frame elements is the presence of a diagonal fastening element, the connecting ends are made at an angle of 45° to the longitudinal central axis of the connecting end of the corresponding frame element, and the two frame elements of the building structures are connected by the edges of their connecting ends, forming an angle of 90° between them. To analyse the stress-strain state of the element, a spatial computer model was developed in the LIRA-CAD software package. The stiffness characteristics of the volumetric finite elements were set taking into account the anisotropic properties of wood in accordance with regulatory requirements. The node was modelled using rod and plate elements. The results of the numerical experiment and testing showed that the node with the proposed connector had sufficient load-bearing capacity.

Key words: research of the connector of the cross-beam structure node, testing of wooden structures.

Introduction. In recent years, there has been considerable interest in the construction industry in the use of glued laminated timber to create cross-beam structures that offer high strength and stability. An important element of such systems are the joints that connect the individual elements and redistribute the forces between them. One solution for fastening elements of cross-beam systems is steel bolt connectors, which can provide high reliability of connections, combining the advantages of both wood and steel. Cross-beam systems involve the use of beams that are connected to each other at a certain angle, which allows for effective load bearing and increased structural rigidity. In such systems, connection nodes play the most important role, because the stability of the entire structure depends on their effectiveness. Connectors that use bolted connections with metal connectors are particularly relevant in cases where it is necessary to increase resistance to dynamic and static loads.

Steel bolt connectors play a key role in connecting wooden elements in cross-beam structures. Bolts ensure the rigidity of connections and contribute to the uniform distribution of stresses in the assembly. They significantly increase the strength of the structure, as they are able to effectively resist torsion, tension and compression that occur at the beam joints. They can be used both for connections within a single beam and for connections between different structural elements, such as beams and posts. Importantly, bolted connections with steel connectors have high shear strength and ensure the stability of the structure over a long period of time. One of the main advantages of using bolt connectors is the possibility of their precise installation and adjustment, which allows achieving optimal strength of connections. Unlike traditional connection methods, such as adhesive or dowel connections, bolt connectors significantly reduce the possibility of defects occurring during operation and ensure reliability even under heavy loads. In addition, the use of bolted connections simplifies installation and dismantling, which is important for the construction and repair of buildings. Bolts are easy to replace if necessary, which makes the structure easier to maintain. There are many design options for bolt connectors, but none of them can be considered universal. We offer our own design solution and the results of its research by calculating and testing two types of joints.

Analysis of publications on testing methods for components and the nature of their operation. The operation of bolted connectors in cross-beam systems is based on the principle of load transfer through rigid steel elements connecting wooden beams. During operation of the structure, when external loads are applied, the forces are transferred to the connection through bolts and plates. Bolts distribute stress across the entire connection area, reducing the likelihood of defects in the wood, such as cracks or chips. An important aspect is the calculation of the strength of the connections, as incorrect installation or insufficient strength of the bolts can lead to loosening of the joints. Load modelling and calculation of the structural characteristics of joints with bolted connectors are important for ensuring the durability and reliability of cross-beam systems. To assess the strength and stability of joints in cross-beam systems, several factors must be taken into account, such as load types (static, dynamic), joint types, material, and structural design of elements. Mathematical models, such as the finite element method (FEM), allow for accurate analysis of the stresses arising in the joints, as well as the identification of possible critical areas with high stress levels in the connections, which can lead to structural failure. The calculation of a bolted joint includes an analysis of stress distribution based on the determination of the strength characteristics of wood and steel, as well as a check for shear and torsion at the joints. The use of FEM analysis allows all the features of the interaction of structural elements to be taken into account, which significantly increases the accuracy of the calculation and the reliability of the final design solution. The paper 'Strengthening of timber structures with glued-in rods' [1] presents the results of research on wooden structural elements reinforced with glued-in rods and the current state of structural solutions with similar reinforcement. It considers production methods, parameters that ensure the productivity and strength of connections, theoretical principles for assessing their load-bearing capacity, and existing design recommendations. The article 'Sustainable Steel-timber Joints for Framed Structures' [2] is devoted to the study of the mechanical properties of joints between wooden glued panels and steel beam shelves using bolts, screws and glue. The influence of load on shear force and destruction of contact zones is analysed. The test results are compared with analytical calculations. The proposed models can be used for nonlinear analysis of steel-timber elements. Useful information on the operation of nail connections is provided in the paper 'Plug Shear Failure in Nailed Timber Connections Avoiding Brittle and Promoting Ductile Failures' [3]. Based on numerous tests of connections, a model of their operation was proposed, which took into account the influence of the stress state of the fasteners. It was shown that shear failure occurs on the nail furthest from the free end of the wood. Increasing the distance between fasteners reduces the risk of shear failure; the distance perpendicular to the wood fibres is particularly important. The article 'On the types of destruction and strength of steel-wood-steel bolted connections loaded parallel to the fibres' [4] presents the results of experimental studies to assess the strength of bolted connections, in particular those subject to brittle failure. The samples were tested for tensile strength. The test variables included the end distance, the distance between bolts, the distance between rows, the number of bolts in a row, the number of rows, the thickness and type of wood element, glued laminated timber or sawn timber. The connections were tested to failure to observe possible failure modes as the variables were changed. The results show that the current Canadian standard approach to assessing the resistance of wood bolt connections is not optimal. Brittle failure modes such as row shear, group pull-out and splitting were observed. Analysis of the results shows that the longitudinal shear stress at failure is related to a parameter that is a function of the smaller distance (distance between ends or distance between bolts) and the thickness of the specimen. The paper 'Load Distribution among Bolts Parallel to Load' [5] presents the measured load distribution between two, three, five or seven bolts in a row parallel to the direction of the applied load for joints with different widths of the main elements of the timber and two values of the width of the steel connecting plates. In articles [6 -10], existing types of connectors for spatial wooden structures are analyzed. In addition to steel nodal connections, attention is paid to aluminum ones.

The aim of the research. Determine the stress-strain state of the node with the original connector of the cross-beam plate made of glued wood under the influence of static load.

Research methodology. Two samples of the joint connection were manufactured for testing (Fig. 1). The first was a prototype of a cross-beam floor slab joint, supported at the corners, with variable cross-sections of elements ranging from 93 to 58 mm in height and a constant thickness of 28 mm. The second was a control sample with constant cross-sections of elements measuring 93 x 28 mm along their entire length. The material for the samples is grade II glued pine wood.

Fig. 1. Testing of the unit sample

Crosswise – a beam slab of an inter-floor ceiling is a structure assembled from short elements of glued wood, connected by paired connectors at each corner of the structure. The lower surface of the slab structure has a curved flat dome shape (Fig. 2).

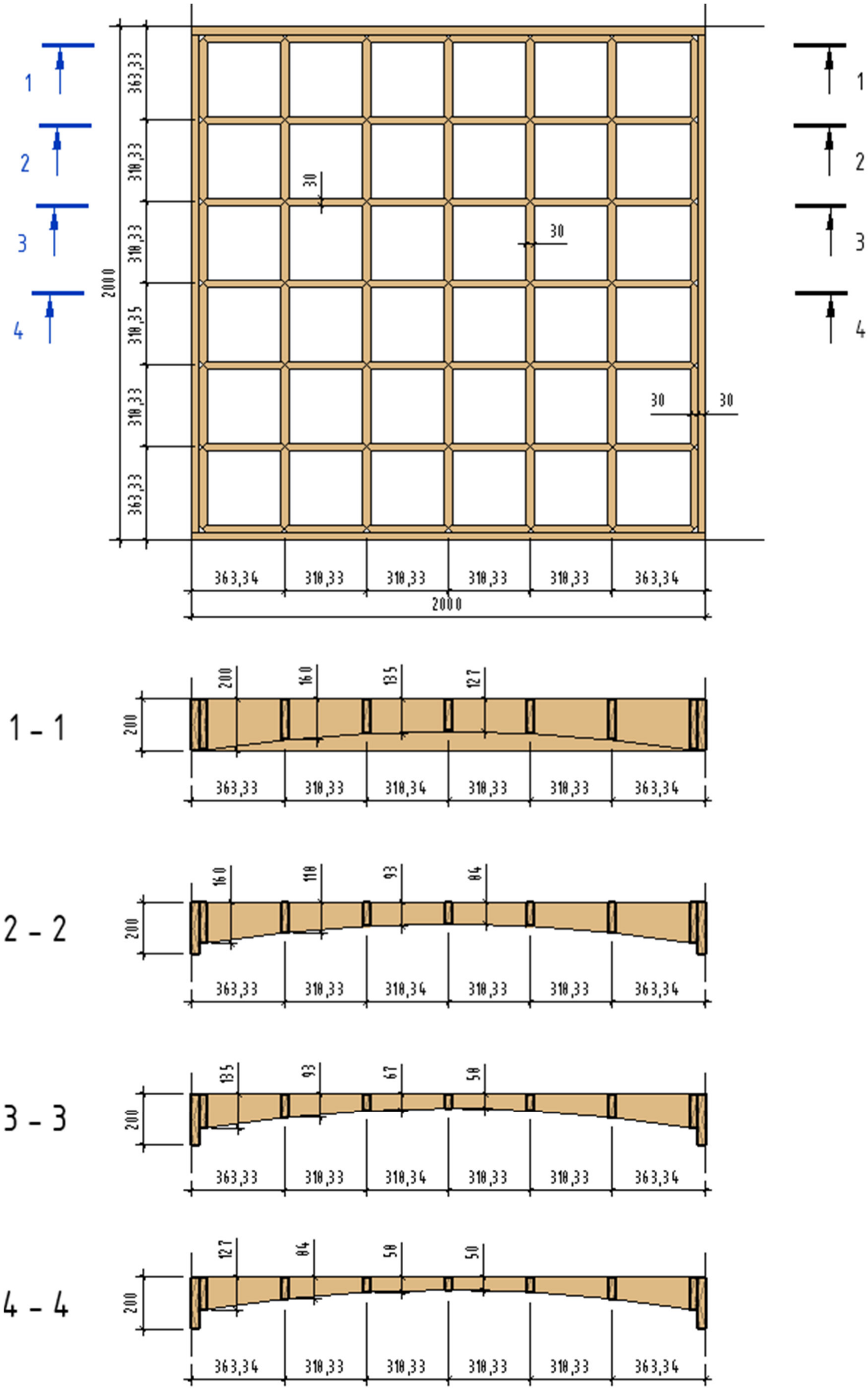


Fig. 2. Structural diagram of the slab

The proposed connector can be considered universal, as it can be used to connect beam elements of various shapes (Fig. 3).

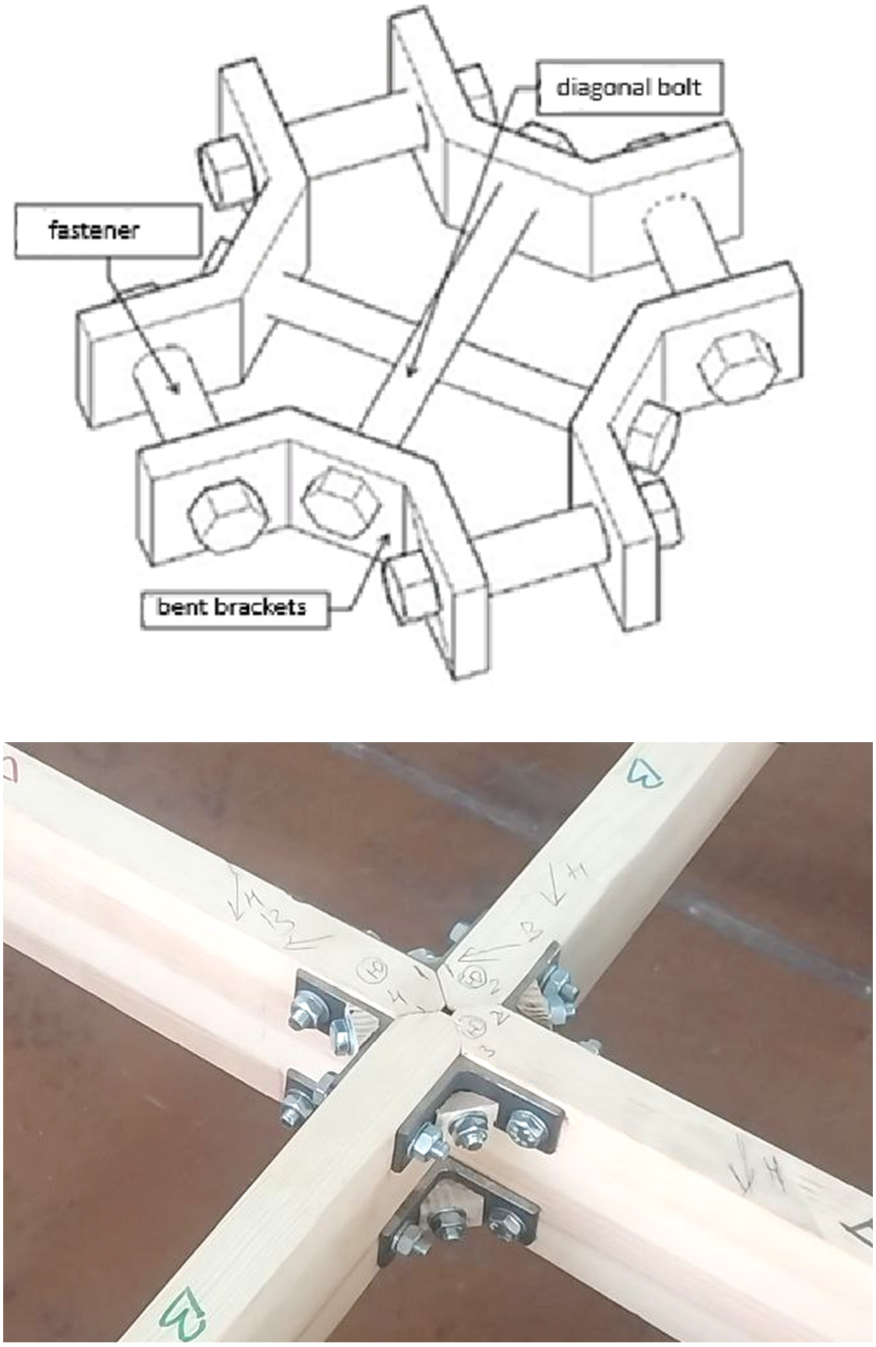


Fig. 3 Universal connector

A distinctive feature of the connector for connecting frame elements is the presence of a diagonal fastening element, the connecting ends are made at an angle of 45º to the longitudinal central axis of the connecting end of the corresponding frame element, and the two frame elements of building structures are connected by the edges of their connecting ends, forming an angle of 90° between them. The invention is based on the task of developing a new, more reliable and simplified universal connector for frame elements and a method for assembling a universal connector for frame elements with increased stability using standard elements, such as an angle-holding node and fastening elements, which will allow elements to be joined at right angles, significantly expanding the creative possibilities for architects, designers and customers. This solution is particularly relevant in the context of current trends in resource conservation, as the design and its ergonomic plastic form contribute to savings in materials and time. The advantages of its use include the improvement of connections in architecture and design, the creation of connections that allow various tasks to be performed in the field of architecture and interior design, and the ability to design and install virtually any surface consisting of frame elements, which is especially important when constructing buildings with non-standard shapes. A new simple way of connecting two, three or four frame elements allows you to change structures directly on site. The connection may be required when constructing surfaces of various shapes, including flat, vaulted, cross-shaped vaults, ruined, etc. The technology allows the construction of stratodesic dome systems, hyperbolic paraboloids and other complex geometric shapes. Thus, the connector greatly simplifies the process of designing and installing structures, increasing their functionality and aesthetic appeal.

In accordance with the research objectives, a programme of experimental tests of research samples was developed. Compression tests of samples were carried out in the laboratory of the Department of Metal, Wood and Plastic Structures of the Odessa State Academy of Civil Engineering and Architecture. For the test, a hinged support was created for the ends of the frame elements connected by a connector. The static load was created by laying bricks on the platform, which transferred the load to the connector. The deflections of the centre of the node were measured using a clock-type indicator with a scale division of 0.01 mm and a maximum rod stroke of 10 mm (Fig. 1).

Research results. A spatial computer model was developed in the LIRA-CAD software package to analyse the stress-strain state of the element. The stiffness characteristics of the volumetric finite elements were specified taking into account the anisotropic properties of wood in accordance with regulatory requirements. The node was modelled using beam and plate elements.
Modelling of a node with a constant cross-section using beam elements. Fig. 4 shows the calculation diagram of the node. A KE 10 beam finite element (universal beam finite element) was used for modelling. Each element of the node is divided into 5 parts. The stiffness of all elements is the same.

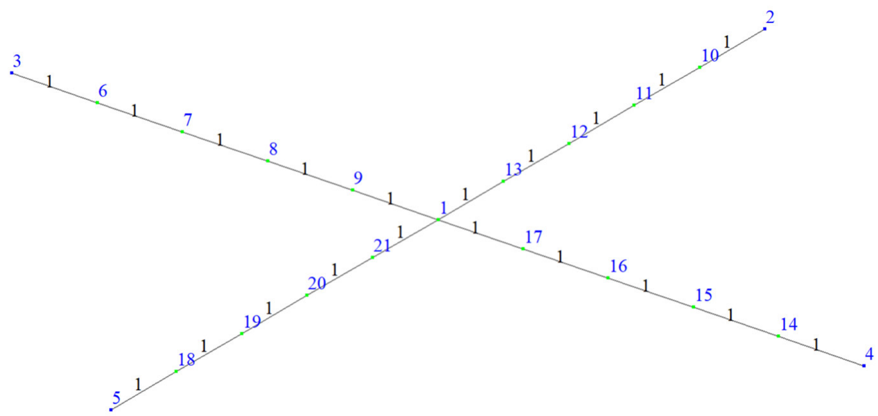


Fig. 4. Calculation diagram of the node with node numbering and stiffness types

Modelling of the node using plates. Fig. 5 shows the calculation diagram of the node. The accuracy of the finite element method calculation directly depends on the types of elements used in the calculation and the level of idealisation of the structure. To compare the calculation results, an additional model of the node was constructed using flat finite elements KE 44 universal quadrangular KE shell. This KE is designed to calculate the strength of thin shells (plates, beams, walls).

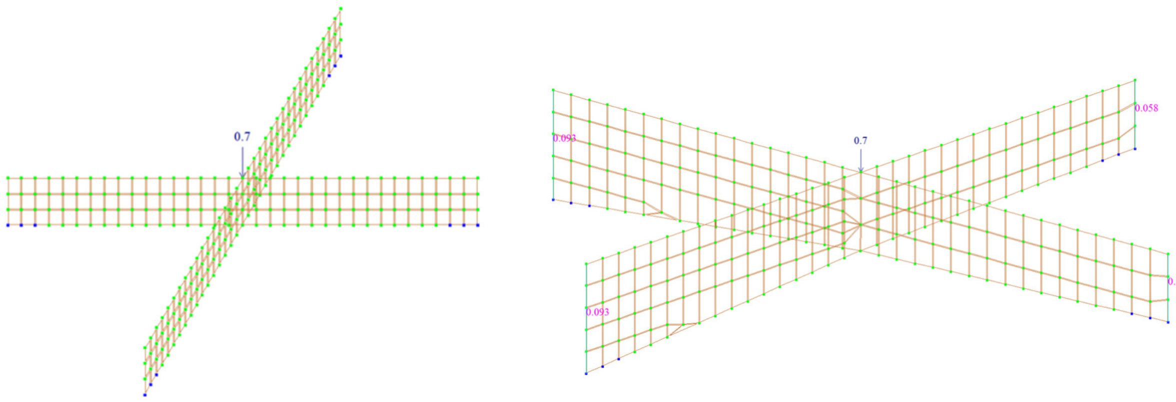
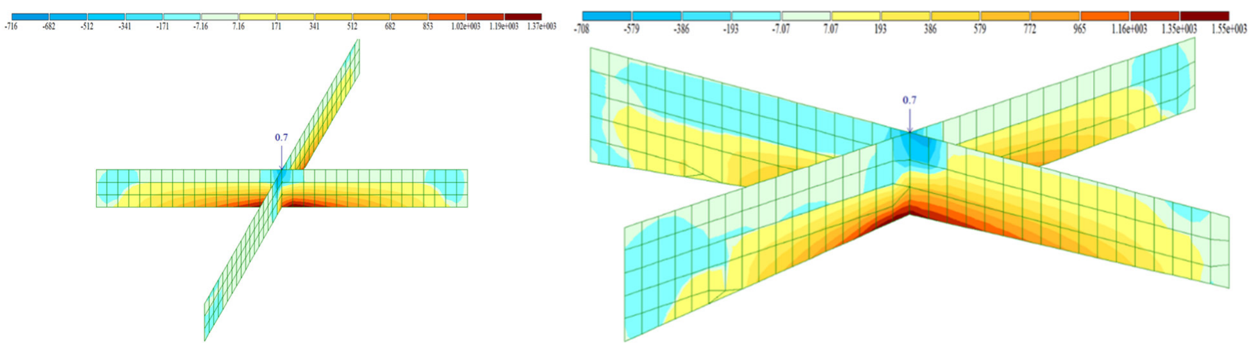


Fig. 5. Calculation diagram of the node using KE44

The load was applied in increments of 0.05 kN, with a total of 12 load steps and a maximum load of 0.7 kN. The calculation resulted in the distribution of stresses in the elements (stress isopoles) and the displacement of the nodes. Fig. 6 shows the stress isopole at the 12th load step, and Figs. 7 and 8 show the displacement of the node centre.



a – constant cross-section   b – variable cross-section

Fig. 6. Calculation results at 12 load steps, σx, kN/m^2

The results of calculations of node displacements with constant cross-section elements and experimental data are presented in Table 1. The deviation of the calculation results from the experimental data was determined. Thus, at the maximum load value of 0.7 kN, the relative deviation in displacement was 31% for the calculation with bar elements and 22% for the calculation with plate elements. It should also be noted that when calculating with bar elements, the displacement is less than the experimental one, and when calculating with plate elements, the displacement is greater than the experimental one, which can be used as a safety margin.

Table 1

Load on the node кН	Vertical displacement, mm			Relative deviation, %	
	Calculation rods	Calculation of plates	Research	Calculation of rods	Calculation of plates
0	0	0	0	0	0
0.05	-0.01957	-0.0354	-0.01	96	254
0.1	-0.03914	-0.0695	-0.05	22	39

0.15	-0.05871	-0.10425	-0.082	28	27
0.2	-0.07829	-0.13901	-0.127	38	9
0.25	-0.09786	-0.17376	-0.152	36	14
0.3	-0.11743	-0.20851	-0.19	38	10
0.35	-0.13701	-0.24327	-0.22	38	11
0.4	-0.15658	-0.27802	-0.242	35	15
0.45	-0.17615	-0.31277	-0.27	35	16
0.5	-0.19572	-0.34753	-0.3	35	16
0.55	-0.2153	-0.38228	-0.325	34	18
0.6	-0.23487	-0.0834	-0.35	33	23
0.65	-0.25444	-0.45178	-0.375	32	20
0.7	-0.27401	-0.48654	-0.4	31	22

Fig. 7 shows a graph of the dependence of displacements on load for experimental and calculated data

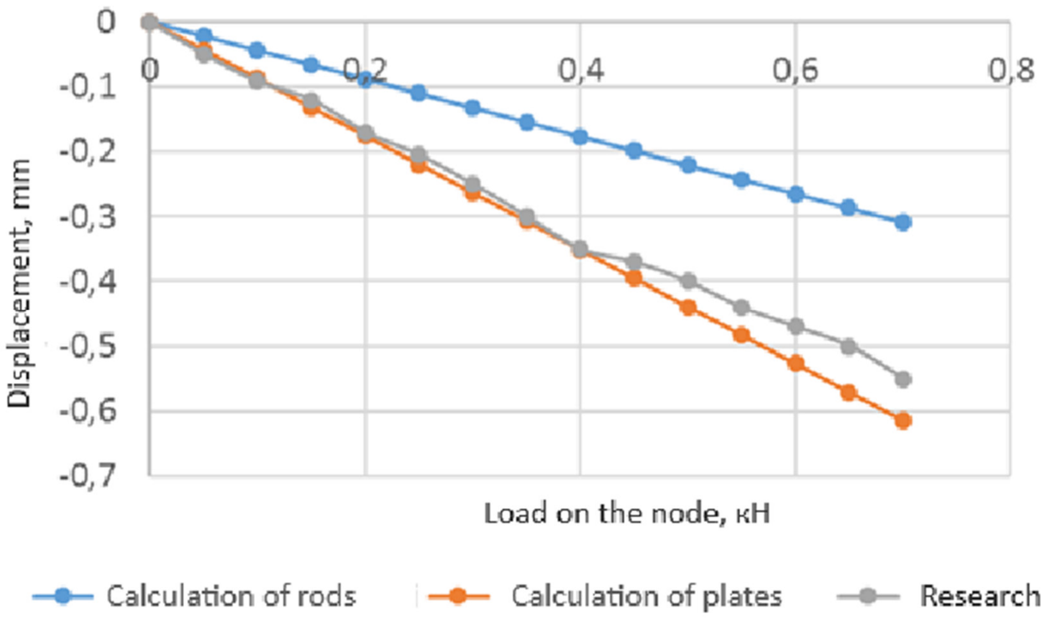


Fig. 8. Graph of the dependence of displacements on load for experimental and calculated data

The results of calculations of node displacements with variable cross-section elements and experimental data are given in Table 2. The deviation of the calculation results from the experimental data was determined. Thus, at the maximum load value of 0.7 kN, the relative deviation in displacement was 44% for the calculation using rod elements and 12% for the calculation using plate elements.

Table 2

Load on the node, кН	Vertical displacement, mm			Relative deviation, %	
	Calculation of rods	Calculation of plates	Research	Calculation of rods	Calculation of plates
0	0	0	0	0	0
0.05	-0.02203	-0.04388	-0.05	56	12
0.1	-0.04406	-0.08777	-0.092	52	5
0.15	-0.06608	-0.13166	-0.12	45	10
0.2	-0.08811	-0.17555	-0.17	48	3
0.25	-0.11014	-0.21944	-0.205	46	7
0.3	-0.13217	-0.26333	-0.25	47	5
0.35	-0.1542	-0.30722	-0.3	49	2
0.4	-0.17623	-0.3511	-0.35	50	0
0.45	-0.19826	-0.39499	-0.37	46	7
0.5	-0.22029	-0.43888	-0.4	45	10
0.55	-0.24232	-0.48277	-0.44	45	10
0.6	-0.26435	-0.527	-0.47	44	12
0.65	-0.28638	-0.57055	-0.5	43	14
0.7	-0.30841	-0.61444	-0.55	44	12

Conclusions

1. The proposed design of an original connector for cross-beam structures made of glued laminated timber.

2. The results of the numerical experiment showed sufficient load-bearing capacity of the node with the connector.

3. Modelling of nodes using different types of finite elements gives different results compared to experimental data. Plate elements provide more accurate displacement results than beam elements.

4. The use of plate elements allows for a safety margin, which can be useful in structural design.

5. The maximum deviation between calculations and experimental data for beam elements is greater than for plate elements, which should be taken into account when choosing a modelling method.

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ДОСЛІДЖЕННЯ РОБОТИ СТАЛЕВОГО ВУЗЛОВОГО КОНЕКТОРА ПЕРЕХРЕСНО-БАЛОЧНОЇ КОНСТРУКЦІЇ З КЛЕЄНОЇ ДЕРЕВИНИ

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Анотація. Перехресно-балочні системи передбачають використання балок, які з'єднуються одна з одною під певним кутом, що дозволяє ефективно сприймати навантаження та підвищити жорсткість конструкції. Вузли, що використовують болтові з'єднання з металевими конекторами, стають особливо актуальними в тих випадках, коли необхідно підвищити стійкість до динамічних та статичних навантажень. В роботі представлені результати дослідження напружено – деформованого стану вузла з оригінальним конектором перехресно – балочної плити з клеєної деревини під впливом статичного навантаження. Для випробування було виготовлено два зразки вузлового з'єднання. Перший – прототип вузла перехресно – балочної плити перекриття, обпертої по кутах, зі змінними перерізами елементів, і другий - контрольний зразок з постійними перерізами елементів по всій їхній довжині. Особливість конектора з'єднання елементів каркасу - наявність діагонального кріпильного елементу, з'єднувані торці виконані під кутом 45° до повздовжньої центральної осі з'єднуваного торця відповідного каркасного елемента, а два каркасних елемента будівельних конструкцій сполучені гранями їх з'єднуваних торців з утворенням кута 90° між ними. Для аналізу напружено-деформованого стану елементу в програмному комплексі «ЛІРА-САПР» була розроблена просторова комп'ютерна модель. Характеристики жорсткості об'ємним скінченним елементам задавалися з урахуванням анізотропних властивостей деревини відповідно до нормативних вимог. Моделювання вузла виконували стрижневими і пластинчатими елементами. Результати чисельного експерименту і випробування показали достатню несучу здатність вузла з пропонованим конектором.

Ключові слова: дослідження конектора вузла перехресно-балкової конструкції, випробування дерев'яних конструкцій.