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EXPERIMENTAL STUDIES OF NODAL JOINTS OF WOODEN ELEMENTS IN TRUSSES AND GEODESIC DOMES

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Abstract

Introduction: In this paper, we consider LVL (laminated veneer lumber with unidirectional veneer) as an element of plane trusses and geodesic domes, acting as the bearing structure of roofs, and study destruction of LVL joints, which is necessary to improve designs of wooden roofs under consideration. **Methods:** Our studies were based on structural mechanics and wood science. In the course of the study, we used analytical, experimental, and statistical methods to process the results of tests. **Results:** Based on the experimental studies performed, we suggest a method to determine the design bearing capacity of treenails per edge joint (conventional shear) for joints of LVL elements with wood laminate (DSP-V, wood laminate where veneer fibers in the adjacent layers are mutually perpendicular) plates. **Discussion:** We obtained new values of the coefficient taking into account the compliance of connections for nodes and joints in LVL composite elements, which make it possible to quickly determine the required cross-sections of bearing rod elements in plane trusses.

Keywords

Construction, wooden roofs, LVL, new nodal joints, laboratory tests, elements of plane trusses, geodesic dome, joints of wooden elements, bearing capacity, treenail.

Introduction

In modern construction, buildings and structures with wooden frames in the roof are less common than buildings and structures with reinforced-concrete and metal elements in the roof. Besides, in most cases, roofs have limited spans, which, in turn, limit the scope of application of wooden frames. Lumber produced out of logs has always been the basic element of structures, and that reduces the efficiency of wood utilization in construction. We suggest replacing lumber produced out of logs with LVL (Zhivotov, 2009a). In this paper, LVL means laminated veneer lumber with unidirectional veneer. LVL has more uniform dimensions and strength properties than regular lumber. This is important in the construction of large-span wooden roofs consisting of arches, frames, and trusses, as well as geodesic domes assembled from LVL members, which are often used not only in construction but also in the reconstruction of buildings in the historical part of Saint Petersburg (Golovina, 2020; Yudina, 2019; Yudina and Tilinin, 2019; Yudina et al., 2019, 2020).

In terms of the construction of wooden roofs with the use of trusses and domes made of LVL, we performed strength tests of new types of LVL joints in plane trusses and geodesic domes in a laboratory environment. We also analyzed the results of previous studies addressing joints of wooden elements.

Methods

The study was based on the science behind wood utilization as a structural material produced as a result of sawing tree trunks (Chernykh et al., 2020, 2022). In the course of the study, we used analytical, experimental, and statistical methods to process the results of the strength tests involving new types of LVL joints in plane trusses and geodesic domes, performed in a laboratory environment.

LVL is made of high-density veneer, where all soft wood layers have fibers in longitudinal direction (Chernykh et al., 2020; Zhivotov, 2009b).

LVL joints in a truss are performed with the use of plates, nails, treenails, and studs (Fig. 1).

First, we conducted experiments to determine the coefficient taking into account the compliance of connections (K_c) for wood laminate (DSP-V, wood laminate where veneer fibers in the adjacent layers are mutually perpendicular) and steel plates.

In the case of many connections in nodes with plates, the coefficient taking into account the compliance of connections (K_c) for wood laminate (DSP-V) plates is used. The viscosity of LVL and wood laminate (DSP-V) joints is determined by viscous mortise bearing resistance.

The pull-out resistance of connections in the joints of truss members with double-sided plates is analyzed with account for the characteristics of the plate:

n — the number of holes in the plate;
b — the width of the plate;
t — the thickness of the plate.

The tensile stresses in the plate are as follows:

$$\sigma_N = \frac{N}{2*A} = \frac{N}{2*(b-d)*t}. \quad (1)$$

The bending moment in the plate at the number of connections n = 3 is as follows:

$$M_{BEND} = \frac{N*5}{2} = \frac{N*t}{4*n}. \quad (2)$$

The bending stress in the plate is as follows:

$$\sigma_M = \frac{M}{W_{PLATE}} = \frac{6N}{4*n*b*t}. \quad (3)$$

The total stress in the plate is as follows:

$$\sigma_{TOT} = \frac{\sigma_N}{R_p} + \frac{\sigma_M}{R_l} \le 1 \quad \text{or}$$

$$\sigma_{TOT} = \sigma_N + \sigma_M \frac{R^{PLATE}}{R^{PLATE}_l} \le R_P \quad (4)$$

$$\sigma_{TOT} = \frac{\sigma_N^{PLATE}}{R_P^{PLATE}} * (1 + \frac{3*R_P^{PLATE}}{n*R_l^{PLATE}}) =$$

$$\frac{N}{2(b-d_c)*t*R_P^{PLATE}} * (1 + \frac{3*R_P^{PLATE}}{n*R_l^{PLATE}}) =$$

$$\frac{N}{2(b-d_c)t*R_P^{PLATE}*m_0*K_C},$$

where $$K_C = \frac{1}{(1 + \frac{3*R_P^{PLATE}}{n*R_l^{PLATE}})}$$

m_0 — the coefficient taking into account the stress concentration effect. In the case of wood laminate (DSP-V), m_0 = 0.9; in the case of steel, it is neglected.

$\frac{R_P^{PLATE}}{R_l^{PLATE}}$ increases the role of the effect of wood material features and takes into account the influence of loading and properties of the material on long-term behavior.

The limit state of the plates can be checked as follows:

$$\frac{\sigma_P^{PLATE}}{K_C * R_P^{PLATE}} \le 1. \quad (5)$$

Based on the equation above, it is possible to determine the coefficient taking into account the compliance of connections (K_c) for wood laminate (DSP-V) plates (Table 1).

Below, we provide values of the coefficient taking into account the compliance of connections (K_c) for steel plates: high-strength plates with yield point σ_y > 38.0 kN/cm² (Table 2) and regular plates with yield point σ_y < 38.0 kN/cm² (Table 3).

The data in Tables 1, 2 and 3 are recommended to be introduced in regulatory standards addressing the design of wooden plane trusses.

Nodal joints were tested with the use of hydraulic and mechanical drives according to a diagram below (Fig. 2).

We aimed to study the effect of the connection type on the bearing capacity of the joint.

During the tests, the following types of connections were considered:

- type 1 — with Casco S9 Super adhesive (by AkzoNobel) over the entire plate, S = 10 cm². Arrangement of the connecting elements: LVL — across the fibers (horizontal), wood laminate (DSP-V) — along the fibers (vertical);
- type 2 — with lag screws (d = 1.2 cm). Arrangement of the connecting elements: LVL — across the fibers (horizontal), wood laminate (DSP-V) — along the fibers (vertical);
- type 3 — with adhesive + lag screws (d = 1.2 cm). Arrangement of the connecting

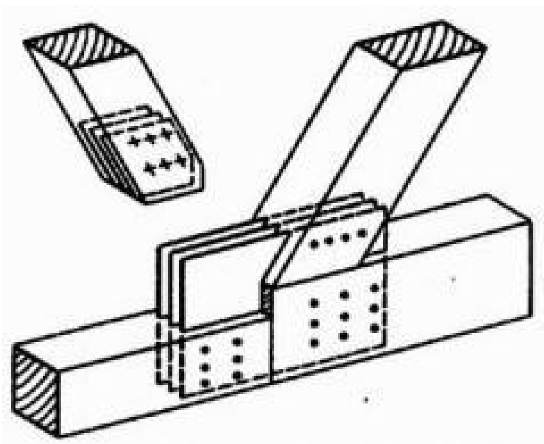


Fig. 1. Truss node with a nailed joint of elements using plates

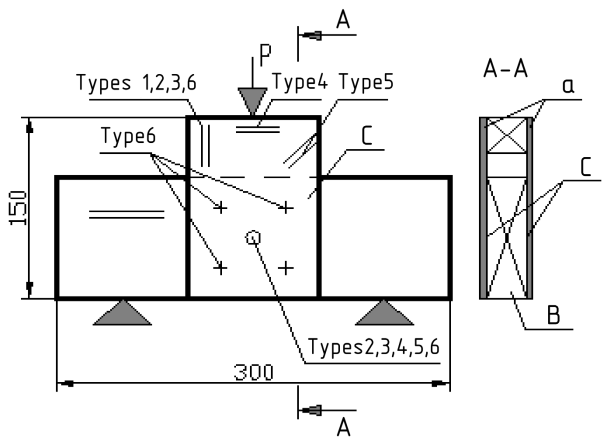


Fig. 2. Diagram of connections at an angle of 90°:
a — wood laminate (DSP-V); b — LVL;
c — adhesive; = fiber direction

Table 1. Values of the coefficient taking into account the compliance of connections for wood laminate (DSP-V) plates

n	1	2	3	4	6	8	10	20
K_c	0.498	0.665	0.749	0.799	0.856	0.888	0.908	0.952

Table 2. Values of the coefficient taking into account the compliance of connections for high-strength steel plates

n	1	2	3	4	6	8	10	20
K_c	0.268	0.423	0.524	0.595	0.688	0.746	0.786	0, 880

Table 3. Values of the coefficient taking into account the compliance of connections for regular steel plates

n	1	2	3	4	6	8	10	20
K_c	0.259	0.412	0.512	0.583	0.677	0.737	0.778	0.875

elements: LVL — across the fibers (horizontal), wood laminate (DSP-V) — along the fibers (vertical);

- type 4 — with adhesive + lag screws (d = 1.2 cm). Arrangement of the connecting elements: LVL — across the fibers (horizontal), wood laminate (DSP-V) — across the fibers (vertical);
- type 5 — with adhesive + lag screws (d = 1.2 cm). Arrangement of the connecting elements: LVL — across the fibers (horizontal), wood laminate (DSP-V) — at an angle of 45° to the fibers (vertical);
- type 6 — with adhesive + lag screws (d = 1.2 cm) + 4 self-tapping screws (d = 0.38 cm). Arrangement of the connecting elements: LVL — across the fibers (horizontal), wood laminate (DSP-V) — along the fibers (vertical).

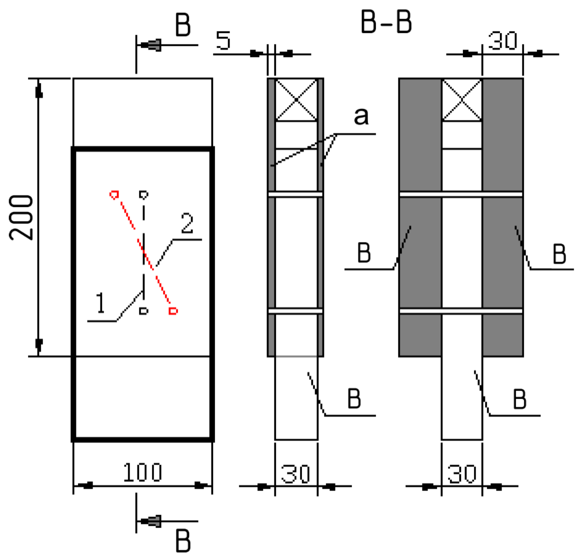


Fig. 3. Diagram of connections along the fibers: a — wood laminate (DSP-V); b — LVL. 1 — the bolts are lined up, 2 — the bolts are in a staggered order

The constructed diagrams imply the following:

1. When types 1, 2, and 3 are compared, the breaking load is as follows:

- with adhesive: 701 kgf
- with lag screws (d = 1.2 cm): 1396 kgf
- with adhesive + lag screws (d = 1.2 cm): 1882 kgf

2. When types 3, 4, and 5 are compared, the breaking load, depending on fiber direction in the plate elements, is as follows:

Type 3. Plates made of wood laminate (DSP-V) with fiber direction along the load axis: 1882 kgf (adhesive + lag screws (d = 1.2 cm)).

Type 4. Plates made of wood laminate (DSP-V) with fiber direction across the load axis: 1687 kgf (adhesive + lag screws (d = 1.2 cm)).

Type 5. Plates made of wood laminate (DSP-V) with fiber direction at an angle of 45° to the load axis: 1528 kgf (adhesive + lag screws (d = 1.2 cm)).

Based on the study conducted, we can assume that fiber direction in wood laminate (DSP-V) elements affects the bearing capacity of the joint and matches the strength properties of the material.

The behavior of elements in treenail joints was analyzed according to a diagram below (Fig. 3).

We aimed to study the effect of connection arrangement on the bearing capacity of the joint for bolts with d = 0.6 cm. For each spacing value, five samples were studied.

We analyzed the behavior of a prestressed treenail by tightening nuts with washers on both sides. The purpose was to study the theoretical prerequisites for an increase in the strength of the joint with prestressing — thrust (Fig. 4). This might be possible due to the reduction of temperature and moisture deformations in LVL.

To avoid torsion of the elements, the samples were made double-shear and symmetrical. The treenails (bolts with d = 0.6 cm of steel 8.8) were set at different spacing *S1* along the fibers. The distance from the vertical axis of the treenail to the edge was more than 3*d* and was equal to 50 mm. Before the tests, dial gauges with a division value of 0.01 mm and a stroke of 10 mm were installed on top of the samples to measure deformations. The load increment was taken equal to 0.1 Pmax.

The bearing capacity of a treenail joint was determined as follows:

Symmetrical joints, bearing resistance in the elements in the middle T^{m}_{b}. (6)

Symmetrical joints, bearing resistance in the elements on the edges T^{e}_{b}. (7)

Symmetrical joints, bending of a treenail made of steel C38/23 T_{bend}. (8)

Based on the shear condition

$$T_{sh} = R^{av}_{sh} * F_{sh}. \quad (9)$$

$$R^{av}_{sh} = \frac{R_{sh}}{1+\beta \frac{l_{sh}}{e}}. \quad (10)$$

T^{m}_{b} (LVL) = 0.5 * c * d * $R_{b,\ LVL}/R_{b,\ wood}$ = 0.5 * 3.0 * 0.6 * 2.3/1.4 = 1.48 kN

T^{e}_{b} (LVL) = 0.8 * a * d * $R_{b,\ LVL}/R_{b,\ wood}$ = 0.8 * 3.0 * 0.6 * 2.3/1.4 = 2.37 kN

T_{bend} (Table 4) $2.7d^2$ = 0.972 kN

Table 4. Bearing capacity in treenail bending at an angle α

α	0°	30°	45°	60°	90°
T_{bend}	$2.7d^2$	$1.8d^2$	$1.7d^2$	$1.6d^2$	$1.4d^2$

$T_{sh} = R^{av}_{sh} * F_{sh}$ = 0.189 * 3.0 * 2.4 = 1.36 kN

$R^{av}_{sh\ (LVL)} = R_{sh\ (LVL)}/(1 + \beta * (l_{sh}/e))$ = 0.24 / (1 + 0.25((4 * 0.6)/(0.25(3.0 + 3.0 + 3.0))) = 0.189 kN

The safety factor *(Ksafe)* was determined as follows:

$$K_{safe} = \frac{{}_{max}*m_{dur}}{T_b}. \quad (11)$$

Thus, the estimated bearing capacity of the entire joint was 4 * 97.2 = 389 kgf. The load increment was taken equal to 150 kgf.

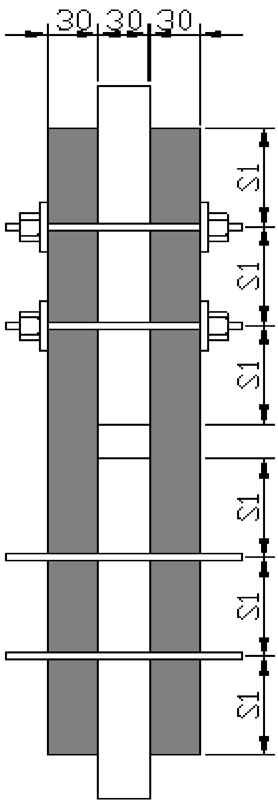


Fig. 4. Diagram of connection arrangement

The tests were carried out using an IM-50 hydraulic press with residual deformation measured. The rate of load increase/decrease was constant throughout the test. During the tests, visual observation was performed and the corresponding test log was filled. After destruction, the fracture pattern was analyzed and photos were taken (Fig. 5). As a result, a deformation vs. load diagram was constructed (Fig. 6).

The measurement results were entered in the test report for LVL (thickness t = 30 mm).

The data obtained were transformed into a diagram showing the relationship between the bearing capacity of a joint and the arrangement of connections (Fig. 7).

The tests showed that in the case of restraint, the LVL joint strength increases by 15%. However, the suggestion to include this theory in regulatory standards will require long-term tests and analysis of the state of nodes in structures operated after several seasons (autumn, spring). This is due to the effect of moisture on the strength properties of LVL.

To study how the connection diameter affects the bearing capacity of the joint, we performed tests using treenails of different diameters. Fig. 8 shows a sample loading pattern.

The tests were carried out using an IM-50 hydraulic press. During the tests, visual observation was performed and the corresponding test log was filled.

The bearing capacity of a treenail joint was determined by Eqs. 6, 7, 8, 9, and 10.

The measurement results were entered in the test report for LVL (thickness t = 30 mm).

The data obtained were transformed into a diagram (Fig. 9).

Since we considered a combined roof consisting of plane trusses and a dome, then in addition to tests for lumber joints in plane trusses, we also performed strength tests involving a new nodal joint of an LVL geodesic dome.

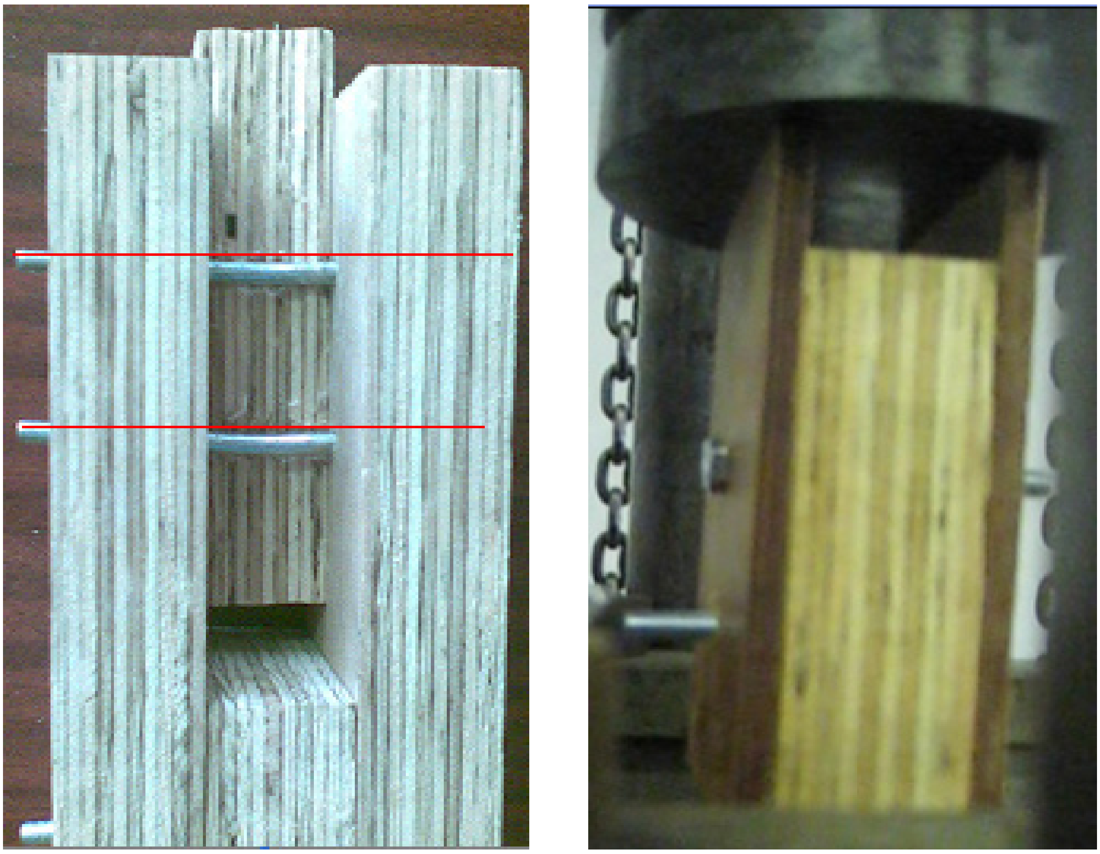


Fig. 5. A sample destroyed

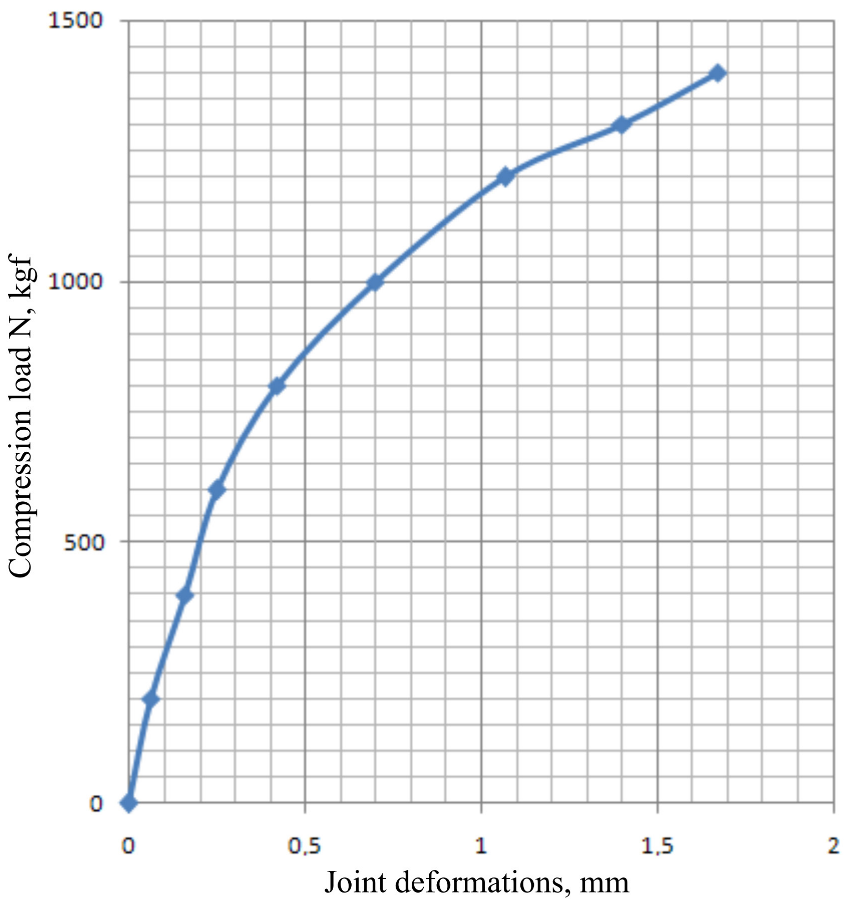


Fig. 6. Deformation vs. load diagram

We considered new patented fiberglass nodal joints (Bushin et al., 2017) tested in a laboratory environment. The node elements were made of TOTAL GF-30 (N) plastic and assembled into a single node, which then was tested under the maximum load of 8.56 kN with an Instron 5998 tensile strength tester (Figs. 10–12).

Fig. 12 shows a destroyed sample, whose elements were made using additive manufacturing techniques.

Results

Based on the studies performed, we suggested a method to determine the design bearing capacity of treenails per edge joint (conventional shear) for joints of LVL elements with wood laminate (DSPV) plates, considering the coefficient taking into account the compliance of connections (K_c) for wood laminate (DSP-V) plates. The results are presented by diagrams showing the relationship between the bearing capacity of the joint and the arrangement of connections as well as the relationship of the breaking load P_{max} and the safety factor K_{safe} with the connection diameter.

These tests of new nodes of geodesic domes are pilot and require further research.

Discussion

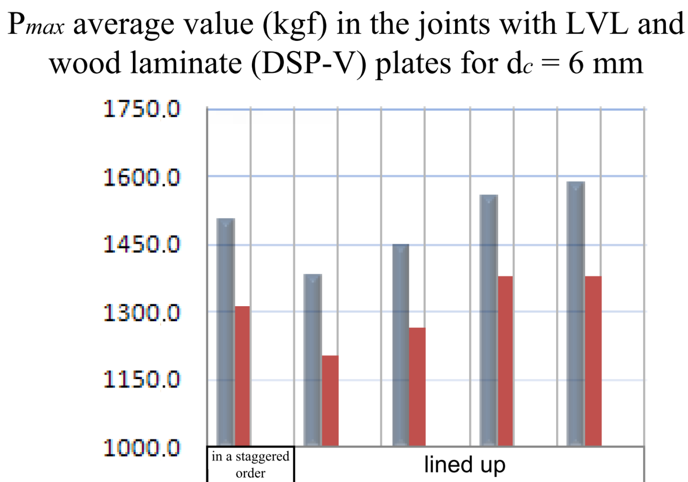
The obtained positive results of testing nodal joints in plane trusses and spatial structures in the form of LVL geodesic domes can be used in the design of wooden roofs in the form of a dome with a diameter of 24 m, resting on the elevated edge of single-slope trusses with a length of 24 m, thus forming a building round in plan with a roof having a diameter of 72 m.

In this paper, equations to determine joints of LVL elements with wood laminate (DSP-V) and LVL plates were proposed.

We established patterns showing the influence of the breaking load P_{max} on the type and diameter of connections as well as method of their arrangement in the joints of LVL elements.

A new design of nodes was proposed. The static tests involving real structures confirmed the effectiveness of the proposed solution for wood laminate (DSP-V) plates under the influence of various aggressive environments.

Further research should include preliminary studies aimed to develop software for the design of nodal joints in trusses with the use of standard elements to reduce material consumption and cut costs. It should also include experimental studies of the new nodal joint of geodesic domes.



	in a staggered order	lined up			
	4d	4d	5d	6d	7d
Pi, kgf (with nuts)	1501.8	1377.8	1446.7	1553.3	1583.3
Pii, kgf (without nuts)	1312.7	1204.3	1263.3	1380.0	1380.0
k=Pi/Pii	1.14	1.14	1.15	1.13	1.15
ratio, %		9%	5%	7%	2%

Fig. 7. Diagram showing the relationship between the bearing capacity of a joint and the arrangement of connections

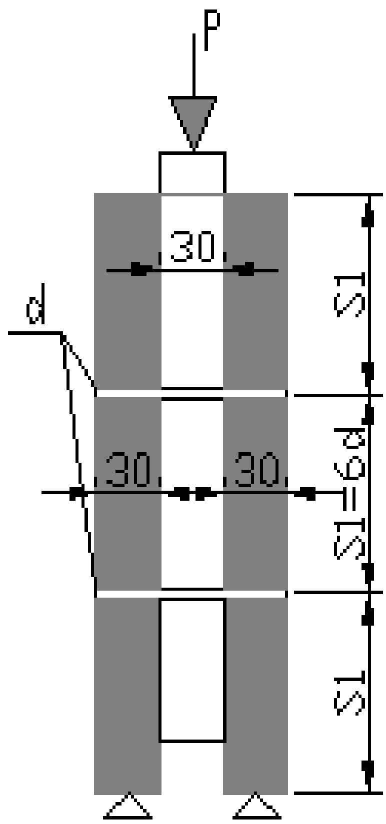


Fig. 8. Sample loading diagram

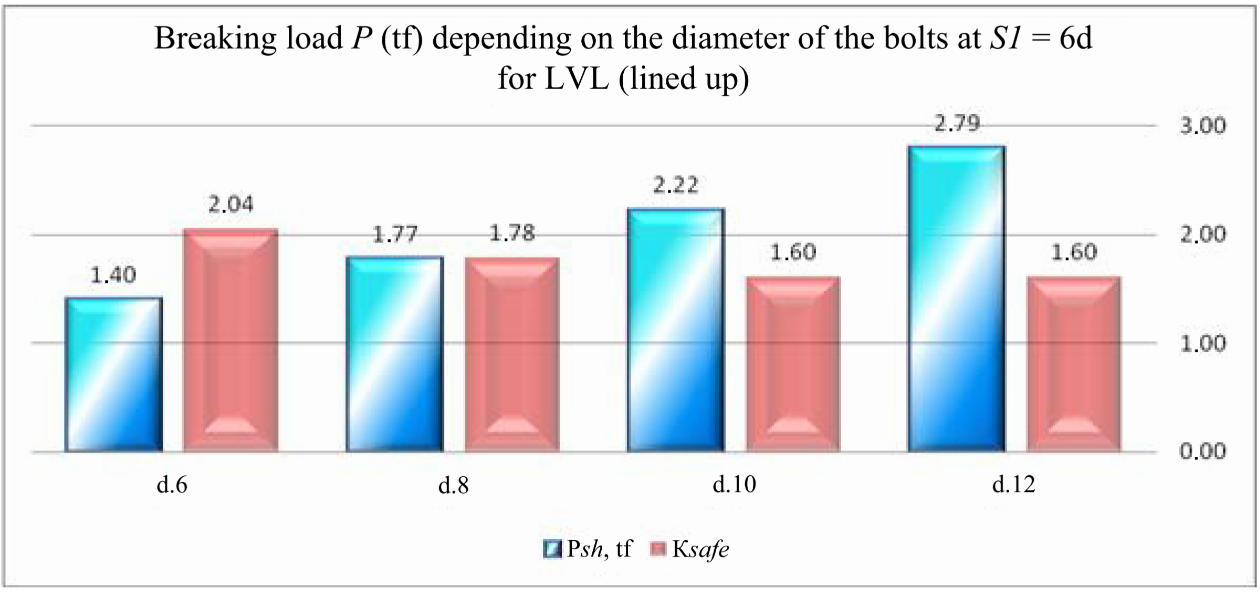


Fig. 9. Breaking load P_{max} and safety factor K_{safe} vs. connection diameter

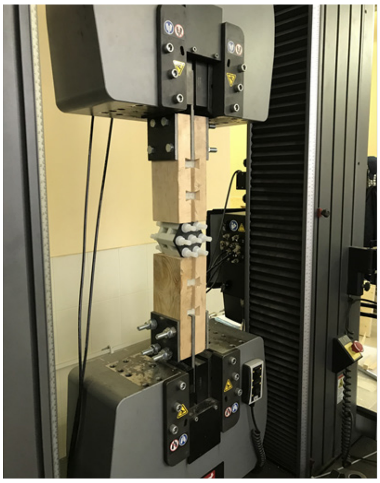


Fig. 10. A sample gripped in an Instron 5998 tensile strength tester

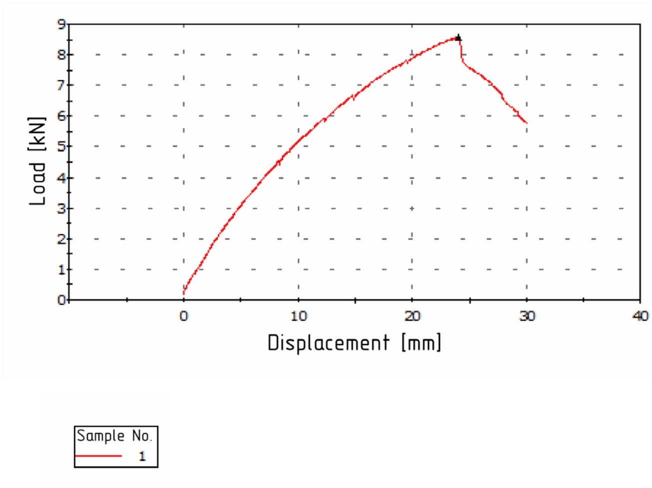


Fig. 11. Displacements vs. applied load

Fig. 12. Node after the tensile test

References

Bushin, V. I., Zhivotov, D. A., and Podolsky, D. M. (2017). *Assembly of bearing rods for geodesic dome and other spatial structures. Patent RU170483U1.*

Chernykh, A., Kazakevich, T., Kiryutina, S., Korolkov, D., and Nizhegorodtsev, D. (2020). Qualification tests of adhesive systems, the assessment of the durability of glued wooden structures. *IOP Conference Series: Materials Science and Engineering*, Vol. 896, 012036. DOI: 10.1088/1757-899X/896/1/012036.

Chernykh, A., Mironova, S., Danilov, E., Mamedov, Sh., Kazakevich, T., and Koval, P. (2022). Determination of deformability of LVL structures with toothed plates connectors. In: Vatin, N., Roshchina, S., and Serdjuks, D. (eds.) *Proceedings of MPCPE 2021. Lecture Notes in Civil Engineering*, Vol. 182. Cham: Springer, pp. 75–83. DOI: 10.1007/978-3-030-85236-8_6.

Golovina, S. (2020). Architectural and constructive concept of the historical residential development of St. Petersburg in the XVIII-early XX centuries. *E3S Web of Conferences*, Vol. 164, 05006. DOI: 10.1051/e3sconf/202016405006.

Guan, Y., Virgin, L. N., and Helm, D. (2018). Structural behavior of shallow geodesic lattice domes. *International Journal of Solids and Structures*, Vol. 155, pp. 225–239. DOI: 10.1016/j.ijsolstr.2018.07.022.

Inzhutov, I. S., Barkov, M. S., Nikitin, V. M., and Ermolin, V. N. (2012). Forming the long-span coating of public bulidings and structures using the dual-slope glued-board elements. *Vestnik Tomskogo gosudarstvennogo arkhitekturno-stroitel'nogo universiteta. Journal of Construction and Architecture*, No. 1, pp. 100–105.

LiveInternet (2011). *R. Bucky Fuller*. [online] Available at: http://eldisblog.com/post198737504/ [Date accessed November 19, 2021].

Yudina, A. (2019). Enhancing technological processes in building construction and reconstruction by means of new technologies. *Asian Journal of Civil Engineering*, Vol. 20, Issue 5, pp. 727–732. DOI: 10.1007/s42107-019-00139-9.

Yudina, A. F., Evtyukov, S. A., and Tilinin, Yu. I. (2019). Development of housing construction technologies in St. Petersburg. *Bulletin of Civil Engineers*, No. 1 (72), pp. 110–119. DOI: 10.23968/1999-5571-2019-16-1-110-119.

Yudina, A. and Tilinin, Yu. (2019). Selection of criteria for comparative evaluation of house building technologies. *Architecture and Engineering*, Vol. 4, No. 1, pp. 47–52. DOI: 10.23968/2500-0055-2019-4-1-47-52.

Yudina, A. F., Verstov, V. V., and Gaido, A. N. (2020). Methodical approaches to the selection of the master theses by specialty 08.04.01 “Construction”, profile “Technology and Organization of Construction”. *Construction and Industrial Safety*, No. 18 (70), pp. 35–42. DOI: 10.37279/2413-1873-2020-18-35-42.

Zhivotov, D. A. (2009a). Determination of LVL strength characteristics. *62nd International Research and Technical Conference of young scientists (PhD and DSc students) and students.* Saint Petersburg: Saint Petersburg State University of Architecture and Civil Engineering, pp. 55–56.

Zhivotov, D. A. (2009b). Plane trusses with the use of LVL. *Industrial and Civil Engineering*, No. 8, pp. 52–53.

Zhivotov, D. and Latuta, V. (2020). Using geodesic domes of wood and thermoplastics for rotational camps in the arctic and northern territories. *Architecture and Engineering*, Vol. 5, No. 3, pp. 22–28. DOI: 10.23968/2500-0055-2020-5-3-22-28.

Zhivotov, D. and Pastukh, O. (2020). Construction of geodesic domes made of wood and composite materials during restoration and conservation of cultural heritage objects. *E3S Web of Conferences*, Vol. 164, 2020, DOI: 10.1051/e3sconf/202016402020.

Zhivotov, D. A., Pastukh, O. A., and Tilinin, Yu. I. (2021). Architectural and spatial planning solutions of spherical shape buildings. In: Rybnov, E., Akimov, P., Khalvashi, M., Vardanyan, E. (eds.) *Contemporary Problems of Architecture and Construction*. London: CRC Press, pp. 91–96.

Zhivotov, D. and Tilinin, Y. (2020). Experimental studies of the strength of nodal joints of geodesic domes made of wood and fiberglass made on a 3D printer for the Arctic and Northern territories. In: Mirola, T. (ed.) *Becoming greener — digitization* *in my work. International Week 10.–14.2.2020. The Publication Series of LAB University of Applied Sciences, part 2.* Lappeenranta: LAB University of Applied Sciences, pp. 57–65.

Zhivotov, D. A. and Tilinin, Yu. I. (2021). Construction of geodesic domes made of wood and plastic. In: Chernykh, A. G. (ed.) *Innovations in Wooden Construction. Proceedings of the 11th International Research and Practice Conference.* Saint Petersburg: Saint Petersburg State University of Architecture and Civil Engineering, pp. 262–268.

ЭКСПЕРИМЕНТАЛЬНЫЕ ИССЛЕДОВАНИЯ УЗЛОВЫХ СОЕДИНЕНИЙ ДЕРЕВЯННЫХ ЭЛЕМЕНТОВ СТРОИТЕЛЬНЫХ ФЕРМ И ГЕОДЕЗИЧЕСКИХ КУПОЛОВ

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Аннотация
Рассмотрен деревянный клееный брус в качестве элемента плоских ферм и геодезических куполов, выполняющего функцию несущих конструкций покрытий зданий, а также проведено исследование разрушения узлов сопряжения клееного бруса, необходимое для совершенствования проектных решений рассматриваемых деревянных покрытий. В работе использовали клееный брус из однонаправленного шпона (LVL - Laminated Veneer Lumber). **Методы:** Исследования базируются на теоретических положениях строительной механики и древесиноведении. В исследовании использован аналитический, экспериментальный методы и статистический метод обработки результатов испытаний. **Результаты:** На основании экспериментальных исследований предложена методика определения расчетной несущей способности нагелей на один шов сплачивания (условный срез) для соединений элементов из LVL с фасонками из ДСП-В. **Обсуждение:** Получены новые значения коэффициентов учета податливости связей в узлах и соединениях в составных элементах из LVL, которые позволяют оперативно подобрать сечения несущих стержневых элементов плоских балочных ферм.

Ключевые слова
Строительство, деревянные покрытия зданий, клееный брус, новые узловые соединения, лабораторные испытания, элементы плоских ферм, геодезический купол, сопряжения деревянных элементов, несущая способность, нагель.