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EXPERIMENTAL STUDY OF A WOODEN GIRDER TRUSS WITH COMPOSITE CHORDS

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Abstract
Introduction: Beam is one of the most common wooden structures. The use of beam structures is relevant in the flooring and roofing of buildings. A disadvantage of using wooden beams is the impossibility to cover a span of more than 6 m without expensive factory-made structures (glued beams, composite beams, metal-and-wood beams, LVL beams, etc.). The study proposes a wooden structure of a composite girder truss with a span of 9 m, assembled from planks with the use of steel dowels directly at the construction site. The **purpose of the study** was to experimentally determine the strength and deformability of wooden girder trusses with a span of 9 m. The following **methods** were used: experimental investigations of the stress-strain state of beams. As a **result**, brittle fracture was noted in the area of the support chord junction with the span chords under the action of breaking load equal to 14.52 kN/m. The values of tensile and compressive strength of wooden girder trusses were experimentally determined to be 35.35 MPa and 25.14 MPa, respectively. The developed wooden girder trusses are recommended for use in the flooring of buildings with a span of 9 m.

Keywords: construction; timber; beam; strength; girder truss; stress-strain state; composite chords.

Introduction

Construction grade timber is one of the most valuable products in engineering. Timber can have economic benefits for construction, as modern timber products are mainly factory-made and brought to the site for rapid assembly. The environmental benefits of using timber structures have been demonstrated in a significant number of projects around the world (Lukina et al., 2022b).

Studies on microstructure and mechanical properties (Lukina et al., 2022ba) show that the molecular and cellular structure of wood is fundamental to its use as a building material.

The use of wooden beam structures in the flooring and roofing of buildings is especially relevant in low-rise individual housing construction (IHC). Such structures can reduce the load from horizontal bearing structures on the walls and foundations of a building since wood is lighter than reinforced concrete cast-in-place and prefabricated slabs in terms of specific weight. This is especially in demand in wall structures when not engineering bricks but less durable light-weight energy-efficient blocks made of expanded clay aggregate, aerated concrete, wood concrete, etc. are used, currently utilized in the construction of more than 85 % of all IHC buildings. However, the use of wooden structures in the flooring and covering of IHC buildings is limited by a number of features. These include issues of structural specifics (anisotropy, flaws, etc.), durability, biological resistance, fire hazard, etc. The main factor leading to an end user's refusal to use wooden structures in the flooring and roofing of buildings is the impossibility to construct spans of more than 6.0 m without additional supports, i.e., limitations in the assortment of solid wood lumber. If steel and reinforced concrete structures are not taken into account, then premises with a width exceeding 6.0 m can be constructed with the use of glued wooden structures, composite wooden structures, metal-and-wood beams, LVL beams, etc.(Nadir et al., 2016). However, the use of such structures results in higher construction costs since all of the above products are manufactured at factory. Among other disadvantages of these structures, their massiveness can be mentioned, which inevitably leads to aesthetic discomfort (pressure on a person) if these structures are arranged in an open form (without lining) in the roofing.

Beam is one of the most common building structures made of timber (Koshcheev et al., 2018; Lukina et al., 2021). Depending on the production method, there are the following types of these structures: beams of solid section made of logs, bars or boards (Autengruber et al., 2021; Ianasi, 2015; Keenan, 1974; Li et al., 2017; Mungwa et al., 1999; Song and Lam, 2010); composite beams made of logs, bars or boards connected on pliable joints (dowels, nails, dowel plates, keys, etc.) (Jiao et al., 2017; Pulngern et al., 2010; Qi et al., 2017); glued

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beams made of boards (Asyraf et al., 2020; Foliente and McLain, 1992; Xu et al., 2024) [14,15,16]; wood-composite structures combined from different materials: (wood-and-metal) HTS I-beam; beams reinforced with steel elements, carbon and glass fiber materials, etc.) (Borri et al., 2005; De Jesus et al., 2012; Issa and Kmeid, 2005).

The use of wooden beam structures in the flooring and roofing of buildings is especially relevant in low-rise individual housing construction due to their physical and mechanical properties, relatively low price, and no need to use lifting and transportation equipment during installation (Anshari et al., 2012; Bocquet et al., 2007). However, these structures also have a number of disadvantages: structural specifics (anisotropy, flaws, etc.), durability, biological resistance, fire hazard, etc. The main factor leading to an end user's refusal to use wooden structures in the flooring and roofing of buildings is the impossibility to construct spans of more than 6 m without additional supports, i.e., limitations in the assortment of solid wood lumber (El-Houjeyri et al., 2019; LeBorgne and Gutkowski, 2010). If we consider only wood-based structures, it is possible to cover a span of more than 6 m only with glued wooden structures, composite wooden structures, metal-and-wood beams, LVL beams, etc. However, the use of such structures results in higher construction costs since all of the above products are manufactured at factory. Among other disadvantages of these structures, their massiveness can be mentioned, which inevitably leads to aesthetic discomfort (pressure on a person) if these structures are arranged in an open form (without lining) in the roofing (Ehtisham et al., 2024; Karelskiy et al., 2015).

This study proposes a structure of a composite lattice girder truss with a span of 9 m, assembled from planks with the use of steel dowels directly at the construction site. The structural design of the girder truss was based on the behavior of structures in bending, to ensure resistance to the maximum forces at all sections. The beam structure makes it possible to use lumber with almost no residue: in 48 m (8 planks of 6 m each), only 18 cm are not used in the structure. Depending on the quality of wood and its processing, pine (*Pinus sylvestris L.*) lumber of grades I–II can be used in the girder truss. Besides, due to its lattice structure, the girder truss has an artistic and aesthetic appearance, which makes it possible to use it in an open form in the roofing.

The use of such a structure in the flooring and roofing of buildings is quite a new direction and requires special studies to determine the strength and deformability of the beam.

The purpose of the study was to determine the strength and deformability of wooden lattice girder trusses by conducting experiments on structure models. The subject of the study is the stress-strain state of a wooden lattice girder truss.

The results of the study make it possible to justify the use of wooden beam structures in the flooring and roofing of buildings with spans of more than 6 m.

Methods

The structural design of the girder truss was based on the behavior of structures in bending, to ensure resistance to the maximum forces at all sections. The girder truss with a span of 9 m (Fig. 1) represents a lattice structure similar in appearance to a wooden truss with parallel chords. Due to the small construction height, this element is considered a beam element (Cao et al., 2020), but for convenience, hereinafter the elements are called truss elements (chord, post, brace).

The girder truss consists of 4 span chords, 4 support chords, 18 braces, and 4 posts. It should be noted that the beam is assembled from eight 6000x150x50 mm planks with almost no residue, which is 176x150x50 mm. This implies that the lumber is 99.96 % utilized.

Between the span chords, braces are installed in the middle of the section at a 3 m long section at an angle of 50°. In the remaining space (1.5 m each) between the span chords, support chords are installed. At the free ends of the 1.5 m long support chords, braces in the form of a lattice at an angle of 50° are installed on both sides. At the ends of the girder truss, paired posts are installed between the chords. The structural elements are connected by dowels: Ø 8 in the support part of the truss, and Ø 12 in the braces. The connection uses paired washers, i.e., washers installed on two opposite sides of the connected element, which ensures high bearing capacity and low deformability of the structure. Flat washers are grouped in sets on both sides coaxially. Due to this, the metal to be joined is pressed evenly into the outer washer around the perimeter. Otherwise, skewing of the bolt body and, as a consequence, incomplete metal pressing-through around the perimeter are possible (Prosyanikov, 2016).

The action of the maximum bending moment in the middle of the span is taken up by the double section of the span chord, the action of the maximum shear stresses in the near-support areas is taken up by the double wall of cross braces, and the action of the support reactions is taken up by the double braces at the ends of the truss.

To confirm the results of the previously conducted engineering and numerical calculations for the wooden girder truss, it was necessary to conduct an experimental study (Alekseytsev et al., 2019), which makes it possible to identify the features of the stress-strain state, reveal the nature of the failure of such structures, and determine the breaking load.

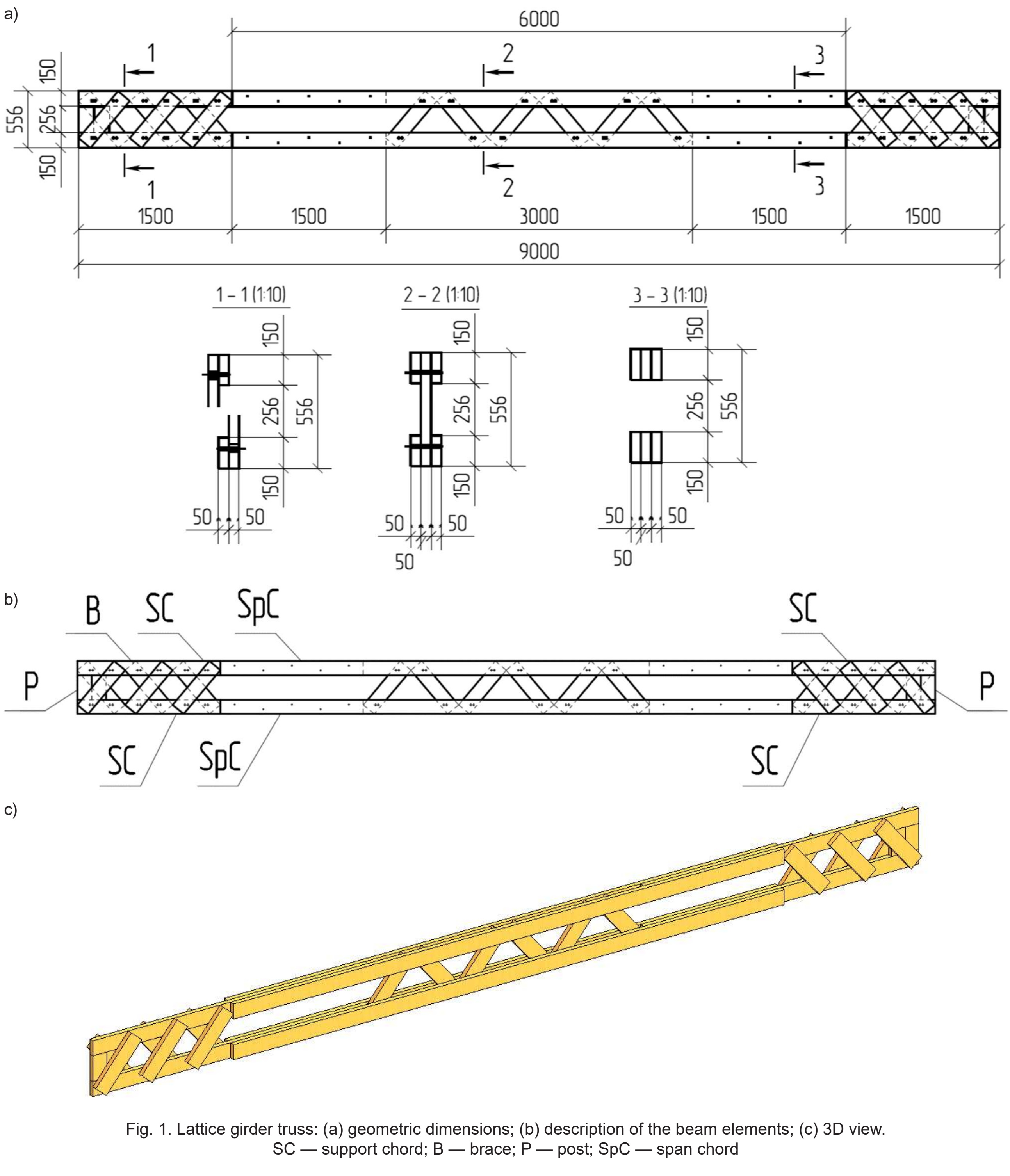

Fig. 1. Lattice girder truss: (a) geometric dimensions; (b) description of the beam elements; (c) 3D view.
SC — support chord; B — brace; P — post; SpC — span chord

The test rig (Fig. 2) developed at the Department of Building Structures and Architecture (Vladimir State University, Vladimir) is designed for testing models of building structures with a maximum span of 4.5 m. Eight-point loading with 0.5 m spacing is performed, which simulates load uniformly distributed over the entire span. Load is directly applied to the structure by means of a system of rods and flexible hangers connected via a shaft/reel to the basket with weights. Load conversion ratio n = 8.5.

Based on recommendations for testing wooden structures, the loading increment can be set within 0.2–0.25 of the design load. This loading corresponds to stress increase in bending in the range of 2–3.25 MPa and relative strains of 26×10^{-5}–32.5×10^{-5}. A TDS-530 multi-channel measuring complex was used to record relative strains with high accuracy. This complex makes it possible to record edge strains of materials by using strain gauges with a base of 20 mm. The latter are glued to the pre-

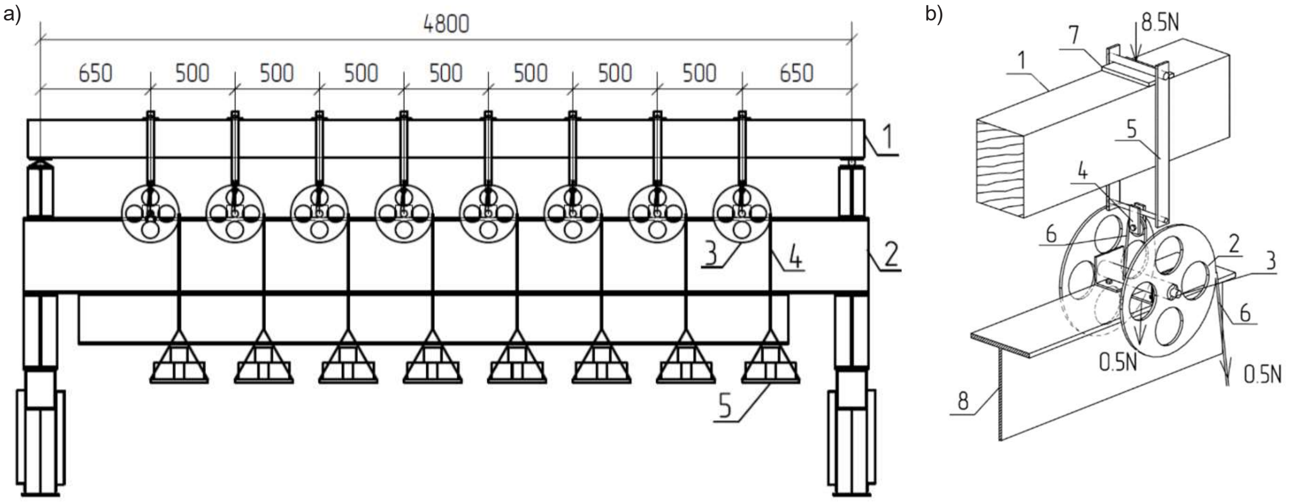

Fig. 2. Diagram of the test rig for testing beams with a span of 4.5 m: a) geometric dimensions; b) principle of the shaft/reel operation. (a) 1 — full-scale beam model; 2 — reactive beam: I-beam No. 45 + I-beam No. 30B1; 3 — connection shaft/reel; 4 — steel cables ø 6 mm; 5 — baskets with weights; 6 — dial gauges, 7 — PAO-6 deflection meters to measure rotation angles of support sections, 8 — PAO-6 deflection meter to determine beam deflections. (b) Design of the shaft/reel to transfer loads to the composite beam with conversion ratio n = 8.5: 1 — beam; 2 — connection reel ø 340 mm; 3 — connection shaft ø40 mm; 4 — single block for cable ø50 mm; 5 — rod made of rolled plate δ = 5 mm; 6 — steel cables ø 6 mm; 7 — distributing plate δ = 16 mm; 8 — reactive beam: I-beam No. 45 + I-beam No. 30B1)

cleaned and treated surface of wooden elements using cyanoacrylate-based adhesive.

The theoretical basis of modeling is the theory of similarity (Mastachenko, 1974), which establishes certain relationships between geometric dimensions, material properties, loads and deformations of the model and the full-scale structure. Simple and extended similarity can be distinguished. In case of simple (linear) similarity, the ratios of all dimensionless quantities are equal to 1, in case of extended (non-linear) similarity, they can differ from 1, and different quantities of the same dimension can have different ratios.

Since the wooden lattice girder truss has a span of 9 m, and the test rig allows for testing structures with a maximum span of 4.5 m, it was was required to perform modeling of the girder truss. The essence of theory of similarity is that a full-scale object is replaced by an analog (its model) based on that theory (Murata et al., 2007). The study addresses large-scale modeling of the structure with simple similarity at 1/2 ratio. All girder truss and fastening dowel elements are reduced in half. The transition from a full-scale object to a model takes place by introducing a system of proportionality coefficients or conversion ratios.

The moduli of elasticity of the model and the full-scale structure are as follows:

$$E_r = \frac{E_m}{E_n}, \tag{1}$$

where E_m — modulus of elasticity of the model; E_n — modulus of elasticity of the full-scale structure.

Since all geometric dimensions are reduced in half, the following equality applies:

$$L_r = \frac{L_m}{L_n} = \frac{1}{2}, \tag{2}$$

where L_m — model span; L_n — full-scale structure span.

We will load the large-scale model with eight concentrated forces. Then the value of the transformed load on the full-scale structure will be as follows:

$$P_n = \frac{P_m}{P_r} = \frac{P_m}{E_r L_r^2} = 4P_m, \tag{3}$$

where P_m — concentrated force applied to the model; P_n — concentrated force applied to the full-scale structure; E_r — modulus of inelastic buckling; L_r — reduced span.

The deflections of the full-scale structure relative to the model can be determined by the following equation:

$$f_n = f_m \frac{L_n}{L_m} = 2f_m, \tag{4}$$

where L_m — model span; L_n — full-scale structure span.

Results and discussion

The tests were conducted at the laboratory of building structures of Vladimir State University (Vladimir, Russia).

The wooden lattice girder trusses were studied in two stages:

• At the first stage, the stress-strain state of the wooden girder trusses was studied and the nature of failure was determined.

• At the second stage, the integral modulus of elasticity was determined, which, unlike the calculated modulus of elasticity, takes into account the heterogeneity of wood, the influence of flaws, etc.

Fig. 3 shows the arrangement of strain gauges on the structure.

The air temperature in the room during the tests was in the range of 18–22°C, relative humidity — in the range of 50–60 %. Wood moisture content was measured with a Testo 616 electronic moisture meter with a measuring range for wood <50 % with an absolute measurement accuracy of 1.2 % in the measuring range of 7–10 % and 2 % in the measuring range nore than 10 %.

At the first stage, the trusses were loaded up to 0.8 of the standard load, in steps of 0.1 of the upper limit. At the second stage, they were loaded until failure, in steps of 0.25 of the design load. Loading time at each step is assumed to be 3 minutes, time of holding under the load is 15 minutes according to the requirements of the testing standard.

The design load was determined based on the condition of strength of normal sections in the middle of the span and amounted to 1.5 kN/m. Four identical models of beam structures (WLB 1...4) were tested. The digit in the girder truss marking indicates the serial number of the model.

Figs. 4 and 5 show the general views of the studied girder trusses during the tests and the nature of failure.

Based on the test results, the statistical processing of the experimental data was performed. The test results are summarized in Table 1 and Figs. 6 and 7.

The girder truss failure occurred at the point at the boundary of the upper support chord junction with the span chords in the form of cut fibers of the near-knot cross-grain and along the flaws in the form of knots. The failure occurred in the upper chord as a result of bending forces. It should be noted that tensile and compressive forces occurred in the upper and lower chords of the girder truss, which was recorded by strain gauges.

Considering the nature of the forces (tension, compression, bending) occurring in the girder truss elements, it can be stated that the developed structure can be classified as a beam although structurally it resembles a truss. The beam showed a quite linear behavior during the tests up to the maximum load achieved during the testing.

The failure was brittle. The average breaking load per unit length was 3.63 kN/m, which exceeds the design load by 2.4 times. To increase the bearing capacity of the girder truss, we propose to install an additional post in the support chord to take up the bending forces. The post will be fastened with metal dowels, similar to the posts in the support part of the structure.

As Figs. 6 and 7 show, the behavior of all tested beams was quite uniform.

Based on the diagram in Fig. 7, we can draw conclusions about the coincidence of the neutral axis of the girder truss with the geometric center of the section. This indicates the symmetrical and simultaneous development of stresses in the compression and tension areas with an increase of the load acting on the structure. Besides, the diagram shows stress points on the top and bottom surfaces of the beam, which lead to the failure of the structure in the tension area under the action of the ultimate load.

The bearing capacity of the tested structures was assessed according to the recommendations for testing wooden structures. The method makes it possible to assess the bearing capacity of wooden beams by calculating the required safety factor depending on the logarithm of reduced time and type of structural failure in a short-term test.

For brittle beam failure, the factor is assumed to be 0.85. Therefore, the design load on the beam will

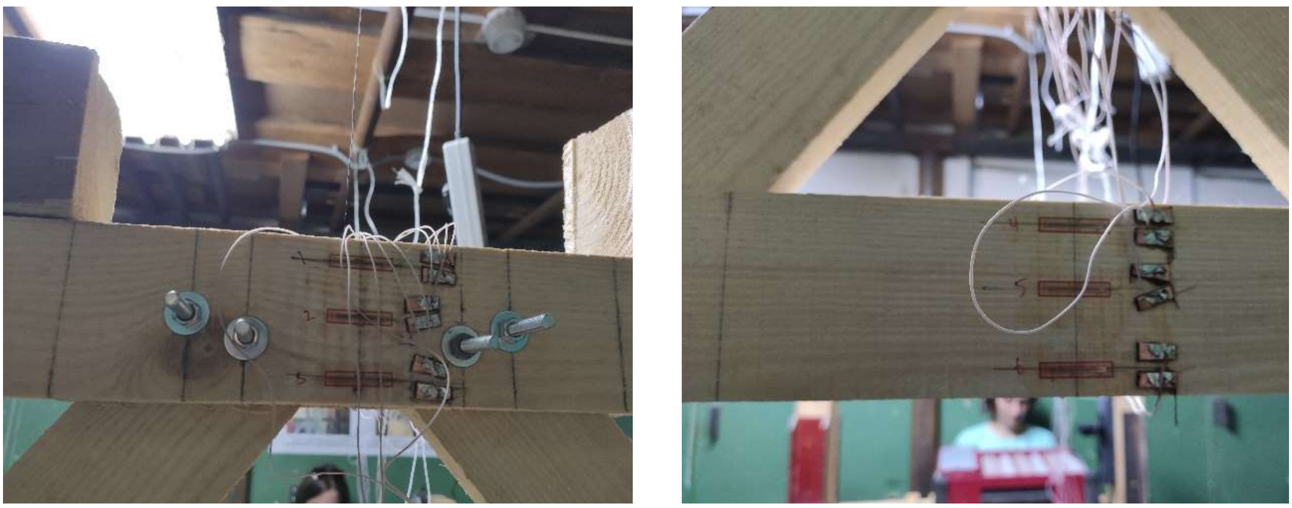

Fig. 3. Arrangement of strain gauges:
a) in the middle of the structure span; b) on the upper and lower span chords, respectively

Fig. 4. General view of wooden lattice beam testing

be 1.275 kN/m instead of 1.5 kN/m, and the maximum allowable load during the design is 3.87 kN/m.

Based on the results of the experimental studies, the breaking load and ultimate deflection of the models of wooden lattice girder trusses were determined. Using Eqs. (3) and (4), it is possible to determine the breaking load and deflection of the full-scale structure during failure, which will amount to 14.52 kN/m and 19.52 cm, respectively.

The tests showed that the joint with the adopted geometric configuration and materials can withstand loads significantly exceeding design ones. The developed girder truss adds versatility to wooden structures and is part of major studies currently conducted around the world to increase the use of structural timber, even in small sizes, obtained as a result of sustainable forestry.

This unique structure was patented in 2022. The use of such structures is possible both in the form of elements in the flooring and roofing of buildings and in the form of temporary elements at the construction site, for example, for formwork construction.

Considering the obtained results, it can be stated that the development and adaptation of scientific and technical solutions to strengthen girder trusses by means of rational reinforcement, mainly in the areas of the support chord junction with the span chords, is a promising approach to improve the performance of the developed wooden beam structure. Composite/reinforced trusses can provide greater strength and stiffness than wooden beam systems, which makes them more suitable for applications with large spans and no columns. Further studies in this direction will contribute to the development of new types of composite building structures with advanced strength and stiffness characteristics.

Conclusions and recommendations

Thus, based on the study of the stress-strain state of wooden lattice girder trusses, the following conclusions can be drawn:

1. A new wooden girder truss with a span of 9 m was developed, which is characterized by easy assembly at the construction site and low installation weight (about 190 kg) at a bearing capacity of 3.87 kN/m.
2. Large-scale modeling (1:2) of the studied wooden girder truss was performed, load and deflection conversion factors (with transition from model to full-scale structures) were determined.
3. Experimental studies of wooden girder truss models under short-term loading on the original test rig were conducted.
4. Tensile and compressive strength of the wooden girder trusses made of pine (*Pinus sylvestris L.*) of grades I–II were determined experimentally, which amounted to 35.35 and 25.14 MPa, respectively.
5. The brittle nature of failure in the area of the support chord junction with the span chords under the action of the breaking load equal to 14.52 kN/m was established, which determines

Fig. 5. Fragment of the general view of the failure area and the nature of failure

Table 1. **Results of wooden lattice girder truss testing**

No.	Beam	Design load, kN/m	Strains, ε×10⁻⁶		Deflections, cm	Breaking load, kN/m
			compression	tension		
1	WLB-1	1.5	2.501	3.587	9.87	3.74
2	WLB-2	1.5	2.439	3.353	9.68	3.52
3	WLB-3	1.5	2.397	3.228	9.53	3.41
4	WLB-4	1.5	2.567	3.760	9.95	3.85

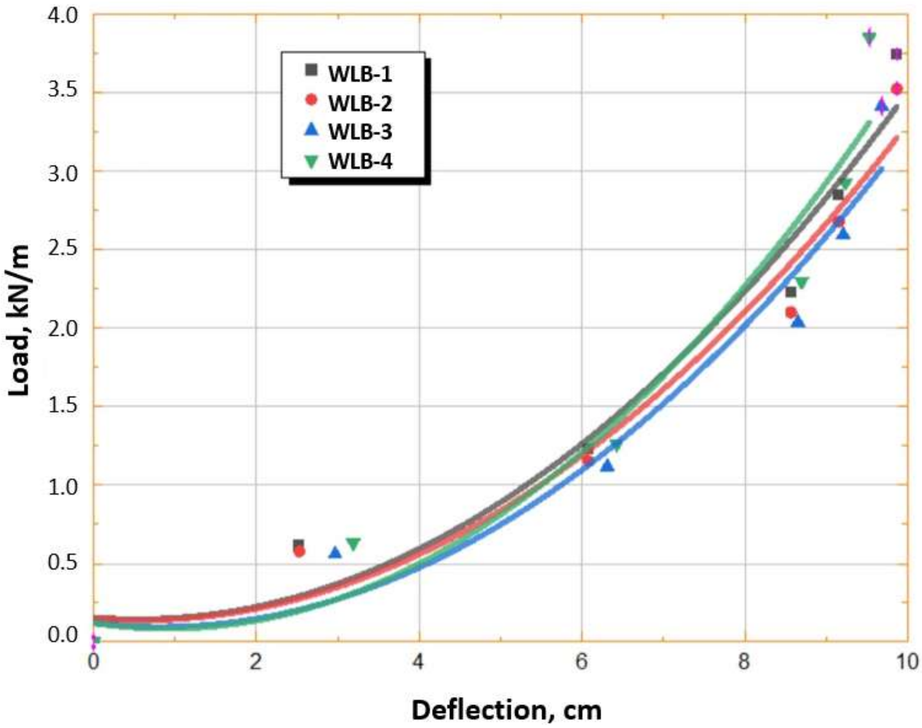

Fig. 6. Load/deflection diagram

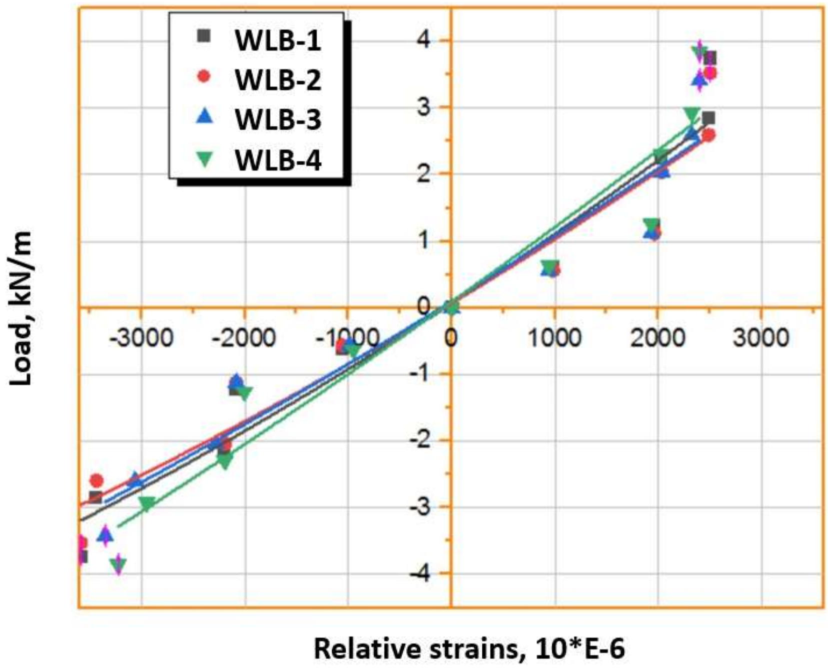

Fig. 7. Load / relative strains diagram

the prospects for further search for scientific and technical solutions to improve the rational layout and structural scheme and its analysis, including the assessment of the influence of the pliable joints of node connections on the stress-strain state of the developed girder truss.

The next stage of research will be devoted to the study of the girder truss under long-term loading to ensure comprehensive reliability assessment of the developed structure.

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ЭКСПЕРИМЕНТАЛЬНОЕ ИССЛЕДОВАНИЕ ДЕРЕВЯННОЙ БАЛОЧНОЙ ФЕРМЫ С СОСТАВНЫМИ ПОЯСАМИ

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Аннотация
Введение: Одной из самых распространенных деревянных конструкцией является балка. Применение балочных конструкций актуально в перекрытиях и покрытии зданий. Недостатком применения деревянных балок является невозможность перекрыть пролет более 6 м без использования дорогостоящих конструкций заводского изготовления (клееных балок, составных балок, металлодеревянных балок, LVL бруса и т.д.). В исследовании предлагается деревянная конструкция составной балочной фермы пролетом 9 м, которая собирается из досок стальными нагелями непосредственно на строительной площадке. **Цель работы** — экспериментально определить прочность и деформативность деревянных балочных ферм пролетом 9 м. Использованы **методы:** экспериментальные исследование напряженно-деформированного состояния балок. **В результате** установлен хрупкий характер разрушения в месте примыкания опорного пояса к пролетным поясам при действии разрушающей нагрузки, равной 14,52 кН/м. Экспериментально определены значения предела прочности деревянных балочных ферм на растяжение и сжатие, равные 35,35 МПа и 25,14 МПа соответственно. Разработанные деревянные балочные фермы, рекомендуется применять в перекрытиях зданий пролетом 9 м.

Ключевые слова: строительство; древесина; балка; прочность; балочная ферма; напряженно-деформированное состояние; составные пояса.