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Composite wooden beams performance under short-term loading

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Abstract. This paper presents an experimental and theoretical study of composite beams made of two balks connected by TGk dowel plates under short-term loading. Composite wooden beams with cross-sections and TGk dowel plate connections are a relatively new solution for building structures and are increasingly used in the construction industry, as they provide high strength and rigidity at a relatively low cost compared to glued beams. The purpose of the study is to confirm the operational strength and rigidity of composite wooden beams on TGk dowel plates, as well as to analyze the stress-strain state of the beams depending on the type of force action and the method of arranging shear ties. To achieve this goal, a target experiment was planned and carried out to test beams made of two bars for transverse load. Beams of different length, three types of transverse load, with different arrangements of shear ties were tested. The beams were destructed under short-term loading in a rather wide range of applied forces, the safety factor fluctuated within 2.13...3.95. After testing the beams using the previously developed method, calculations were performed with linear and nonlinear diagrams of joint deformation. The difference between the experimental and theoretical values of deflections is within 20 %, which quite convincingly confirms the validity of the theoretical calculations.

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1. Introduction

The potential of wood as a material for load-bearing building structures is currently far from being fully realized. The main reason may be the lack of sufficiently effective means of connection that adequately correspond to the structural qualities of wood itself and significantly reduce the impact of its inherent disadvantages.

Due to the rather large volumes of logging, there has been a tendency to reduce the cross-sectional dimensions of natural lumber. It is obvious that the increase in the efficiency of wooden structures is associated with the use of new types of connections that allow an increase in the load-bearing capacity of structures, including through the use of composite rods made of limited-range lumber.

Vyatka State University has developed dowel connectors, which are connecting elements for wooden structures containing a group of cylindrical dowels of increased diameter 5...8 mm with a denser arrangement and fixed on a common base [1–3]. The basic type of connectors (Fig. 1), called TGk metal connector plates, was developed mainly to produce composite wooden elements of increased cross-section. The base of such a connecting plate is made of metal, which is designated by the letter “T”. The letter “G” denotes dowels, pointed at both sides. The dowel is attached to the base by welding, designated by the letter “k”. Therefore, this type of connecting plate is marked TGk [4].

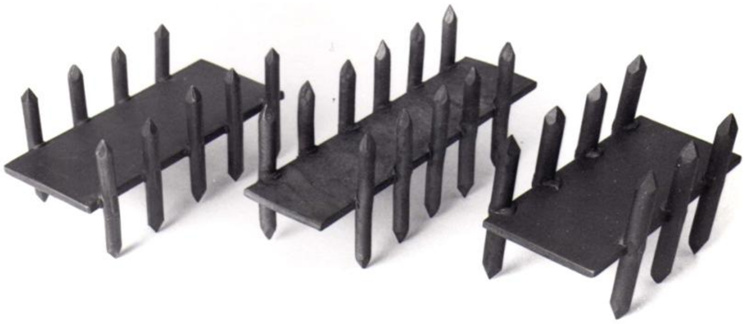


Figure 1. TGk metal connector plates.

The main advantage of such connections is the relative simplicity of manufacture and their functional versatility, which allows for the efficient production of composite beams and nodal joints of wooden structures. In addition, for most climatic regions of Russia, characterized by increased snow loads, such structures are not much inferior to glued structures and rod structures based on the latest types of dowel connecting elements [5–13].

Based on TGk dowel plates, composite elements with various cross-section configurations have been developed. The idea of such rods is to increase the cross-section of wooden elements significantly, using lumber of relatively small diameters. The general appearance of the main types of composite beams with connections on TGk plates is shown in Fig. 2.

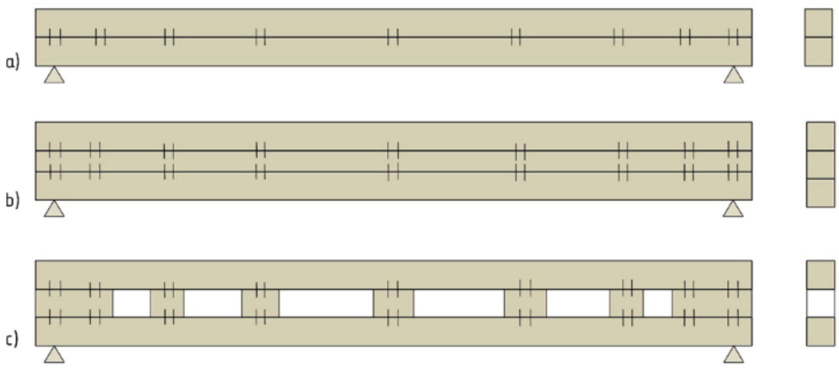


Figure 2. Main types of wooden composite beams: a) made of two beams; b) made of three or more beams; c) perforated composite beams.

Composite elements with connections on TGk dowel plates are considered along with wooden beams of composite section on various mechanical connections, as well as along glued elements of factory production to produce building structures for various purposes: rafter trusses, roof slabs, purlins, wall panels, composite columns, spatial structural forms, etc. Composite elements of type “c” allow saving wood directly, since in the central zone along the height of the cross-section of the element, where normal stresses are minimal, it is possible to significantly reduce the volume of material.

Numerous works [14–24] are devoted to studies on the assessment of the stress-strain state of composite wooden elements and the methodology for their testing, including various connections of composite wooden and composite beams.

Previously, at the first stage of comprehensive studies of connections on TGk dowel plates, short-term mechanical characteristics of dowel nest wood and deformation characteristics of dowel material were determined [25]. The results of experimental and theoretical studies on determining the bearing capacity and deformability of connections under short-term [26] and long-term [27] loading were obtained.

The relevance of further studies is due to the need for an experimental and theoretical analysis of structural elements – wooden composite beams based on the developed connections. The purpose of the research is to confirm the operational strength and rigidity of beams on TGk dowel plates, as well as to study the operation of beams depending on the type of force action and the method of arranging shear ties.

To achieve this goal the following tasks were set:

- to conduct experimental studies of wooden beams with short-term permanent loading;
- to establish the nature of the beams’ operation depending on the type of force action and the method of arranging shear ties based on experimental and theoretical analysis;

- to carry out an experimental verification of the calculation method for composite wooden bending rods with discrete shear ties.

The object of the study is wooden beams of composite cross-section of beams on TGk dowel plates, working on transverse bending.

The subject of the study is the stress-strain state of the proposed type of beams under the short-term loading.

2. Methods

For practical assessment of the bearing capacity and deformability of composite wooden beams, as well as experimental verification of the proposed method for calculating composite rods with discrete shear ties [28], tests of composite beams from two bars with connections on TGk dowel plates were carried out.

Short-term tests were carried out on a special stand for testing beams for transverse bending in accordance with the recommendations for testing wood structures of the Kucherenko Central Research Institute of Building Structures. The beams were installed on two supports: hinged movable and hinged fixed. The load on the beams was transferred by the pressure of a hydraulic jack installed in a rigid frame fixed to a power base. To simulate various types of transverse loads, special distribution devices were used shown in Fig. 3.

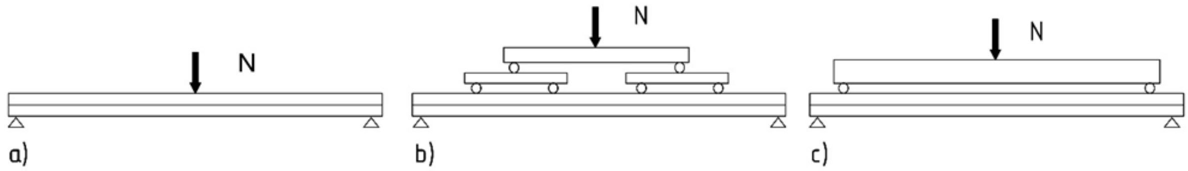


Figure 3. Schemes of application of transverse load during beam testing: a) concentrated load; b) distributed load; c) imitation of support bending moments.

The loading schemes selected are those most frequently used in practice: concentrated force, distributed load and bending moments at the ends of the beam.

During the test the following was determined:

- deflections in the middle of the span and at 2 intermediate points in the quarters of the beam span;
- displacements of the mutual shear of the ties along the shear joint of the bonding at several points along the length of the beam;
- relative deformations of the wood fibers in the section located at 150 mm from the middle of the span, at six points along the height of the beam on both sides.

To measure the deflections, 3 clock-type indicators ICh-50 with a measurement accuracy of up to 0.01 mm and 4 indicators ICh-10 on the supports were installed – to consider the deformations of the wood destructed under concentrated loading. The beam deflection in the span was determined as follows:

$$f_x = f - \left[\delta_1 + \frac{x(\delta_2 - \delta_1)}{L} \right], \quad (1)$$

where δ_1 and δ_2 are the deformations on supports.

The deflection f in the middle of the span was determined by the readings of the average indicator minus half the sum of the readings of the support indicators.

The shifts along the seam (deformations of the ties) were measured by the ICh-10 indicators Nos. 6, 7, and 10–13, which were attached to special devices installed along the plane of the bonding seam before pressing the beams. Indicators Nos. 6 and 7 were installed at the ends of the beams near the supports, and indicators Nos. 10–13 were installed at several points along the length of the beam.

The deformations of the wood fibers were measured using strain gauges with a 20 mm base, glued at 3 mm from the edge of each beam and in the center on the sides. The arrangement of the devices during beam testing is shown in Fig. 4.

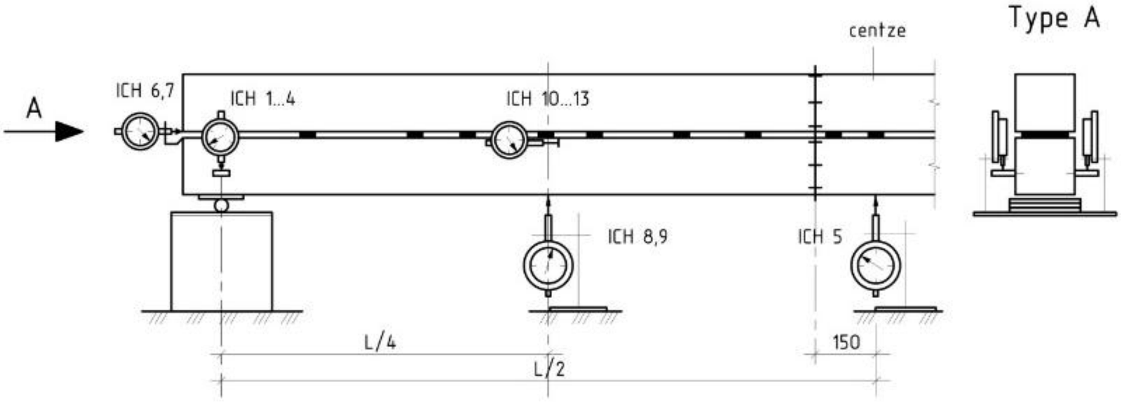


Figure 4. Diagram of the arrangement of measuring devices during beam testing.

The beams were tested at a constant loading rate in steps of 1/6...1/8 of the calculated load on the beam. The loading of a single stage was performed for 1 minute with subsequent readings from the instruments for 2 minutes. Preliminary tests of the 0-series beams were performed with loading up to the calculated value of the applied force with unloading to zero.

The testing of beams of the main series 1 and 3 was carried out in the following mode: loading the beam in stages up to the calculated value of the force, unloading up to the first loading stage, performing several loading-unloading cycles with subsequent unloading to zero, then loading in stages until destruction.

To determine the calculated deflections and edge normal stresses in composite beams, it is necessary to know the elastic modulus in bending E_b of the beams that make up the beam and the local modulus E_w at the spot where the strain gauge is located, since:

$$\sigma = \varepsilon E_w \frac{S_s}{S_w}, \tag{2}$$

where S_s / S_w is the conversion factor, the ratio of the strain sensitivities of the recording station, and the strain gauge.

The local modulus E_w and the elastic modulus in bending E_b of the beams that make up the beam were determined before the production (pressing) of the composite beams. Strain gauges were glued to each beam and loading was carried out with one or two concentrated forces with a span equal to the span of the composite beam. The loading was repeated 4 times in the range of 0.25...1.0 of the design load, the deflection in the middle of the span and the relative deformations of the wood fibers at the locations of the strain gauges were determined. The elastic modulus was determined as follows:

$$E_b = \frac{ML^2}{K_f JF}, \tag{3}$$

where K_f is the coefficient depending on the type of transverse load.

The local elastic modulus was determined for the compressed and stretched zones of the beam from the condition of equality of the external and internal moments in the section where the strain gauges are located:

$$M_{ext} = M_{int} = \int_F y \sigma dF, \tag{4}$$

where y is the coordinate of the beam section under consideration along the height; σ are the stresses in the section under consideration $\sigma = \varepsilon E_w$; ε is the relative deformations of wood fibers.

The deformations of the edge fibers were determined from the known deformations at the locations of the strain gauges from the similarity of triangles:

$$\varepsilon = \frac{h_i\left(\varepsilon_{up(low)} - \varepsilon_{mid}\right)}{h_i - 2a} + \varepsilon_{mid}, \tag{5}$$

where $\varepsilon_{up(low)}$ is the deformation by upper and lower strain gauges; ε_{mid} is the strain on average strain gauge; h_i is the height of the cross-section of the beam; a is the distance from the outermost fiber to the location of the strain gauge.

To determine the maximum stresses in the central section, the deformations were recalculated proportionally to the distance from the center of the beam to the section, in which the strain gauges were located.

3. Results and Discussion

At the preliminary testing stage (series 0), three different composite beams were manufactured on TGk dowel plates. Beam No. 2 is 3.5 m long with a cross-section of 2×140×130 mm, 11 dowel plates are installed at half the length with a minimum pitch in the zone of maximum shear forces – at the beam supports. Beam No. 4 is 2.7 m long with a cross-section of 2×140×125 mm, 5 dowel plates are installed at half the length with a uniform pitch. Beam No. 5 is 3.5 m long with a cross-section of 2×80×80 mm, 8 dowel plates are installed at half the length with a uniform pitch.

The beams were tested repeatedly under various types of transverse loads. They were brought to destruction during the final test with a concentrated force in the middle of the span. The main parameters of beam tests (calculated M_{cal} and destructive M_{dest} bending moments, experimental deflection in the middle of the span f, displacements of mutual shear of ties along the shear joint Δ_{sh}, relative deformations of wood fibers along the upper and lower strain gauges) are given in Table 1.

Table 1. Characteristics of beams of series 0 and main test results.

No.	L cm	$\frac{E_b}{E_w}$ (MPa)	Type of loading	M_{cal} (kN·cm)	Test results (mm) f	Δ_{sh}	ε_{up}	ε_{low}	M_{dest} (kN·cm)
2	350	12473 / 12255	12,5 kN	1094	5.98	0.55	–130	+130	-
4	270	9165 / 12755	8,0 kN	540	3.43	0.22	–69	+78	1563
			4,5 kN	540	4.47	0.30	–57	+65	
			18,0 kN	540	4.95	0.36	–49	+66	
5	350	7622 / 10632	3,5 kN	306	16.8	0.43	–223	+170	1267

Relative deformations for the upper and lower strain gauges in the table are increased by $2 \cdot 10^5$ times.

The beams are usually destructed due to the rupture of wood fibers in the lower (stretched) zone. The safety factor for beam No. 4 was 2.59; for beam No. 5 – 3.52; beam No. 2 was not subject to destruction.

After the tests, the beams were calculated using the method described in [28] with linear and nonlinear diagrams of the bond deformation, which were obtained as a result of previous experimental and theoretical studies of connections on TGk dowel plates [27]. The calculation with the linear diagram $T - \Delta$ was performed for α_t = 0 and α_t = 0,85 cm (α_t is the distance from the bonding seam to the position of the shear force along the height of the beam cross-section). In this case, the possible spread of the deformation characteristics of the shear ties (lower and upper boundaries of the calculated bond deformation diagram) was taken into account. The main calculation results (deflection in the middle of the span f and maximum edge stresses σ) are summarized in Table 2.

Table 2. Comparison of test results of series 0 beams with calculation data.

No.	Parameter	Experiment	Calculation with a line T–Δ	Calculation with a nonlinear T–Δ			
				α_t = 0		α_t = 0.85 cm	
				$\dot{X}$	X_{min} ... X_{max}	$\dot{X}$	X_{min} ... X_{max}
2	f (mm)	5.98	5.64	5.28	5.15...5.50	5.99	5.87...6.18
	σ (MPa)	10.2	9.02	8.85	8.78...8.76	9.46	9.38...9.56
4.1	f (mm)	3.43	2.91	2.62	2.42...2.87	2.98	2.51...3.26
	σ (MPa)	4.94	5.82	5.46	5.27...5.71	5.68	5.47...5.94
4.2	f (mm)	4.47	3.74	3.53	3.23...3.23	3.68	3.38...4.01
	σ (MPa)	4.12	5.01	4.72	4.54...4.59	5.06	4.93...5.30
4.3	f (mm)	4.95	4.03	3.96	3.60...4.33	4.16	3.81...4.51
	σ (MPa)	4.18	4.71	4.53	4.37...4.76	4.95	4.87...5.14
5	f (mm)	16.79	15.59	14.91	14.3...15.7	19.07	18.5...19.8
	σ (MPa)	15.70	11.70	11.20	11.0...11.6	13.10	12.9...13.5

According to the data in the Table 2, it can be concluded that the results of the experiment and calculation are in satisfactory agreement with both linear and nonlinear diagram $T-\Delta$, since all beams were tested in the calculated load range, where the deformation diagram has a significant linearity. It should be noted that the experiment and calculation are in greater agreement when taking into account the value α_t, as well as the calculation by the lower boundary of the diagram when applying a shear force along the edges of the beam-constituting bars.

Based on the preliminary tests of series 0 beams, a target experiment was planned to test composite beams for transverse load. The experiment planning matrix for short-term loading for series 1 and 3 is shown in Fig. 5.

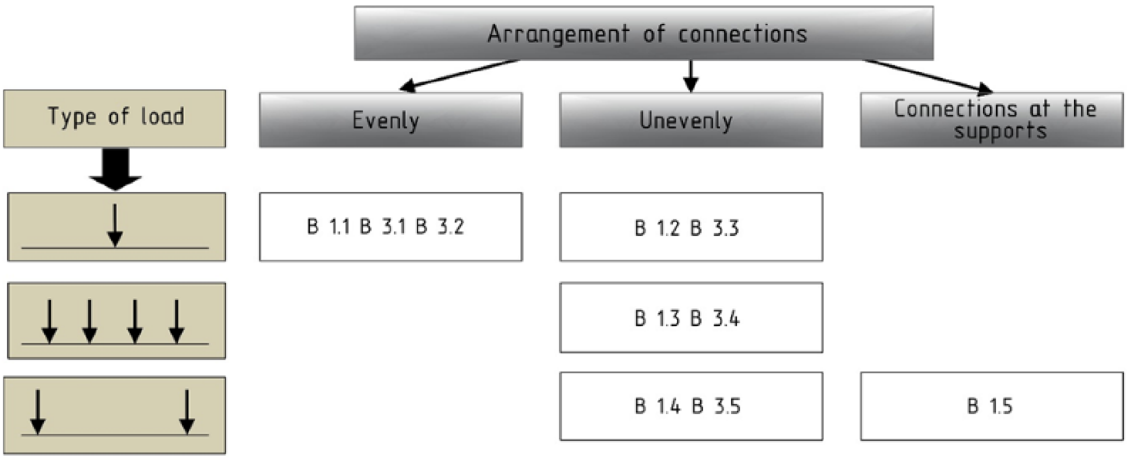


Figure 5. Experiment planning matrix.

In general, the experiment includes testing three series of beams with short-term and long-term loadings. Series 1 and 3 were performed to establish the nature of the work of composite beams depending on the type of force action and the method of arranging shear ties. Series 2 – testing beams with long-term loadings. All beams are made on TGk dowel plates with 5 dowels of 5 mm in diameter and 60 mm in length.

The dimensions of beams of series 1–3 are determined based on the condition of modeling the longitudinal rib of a roof slab with a span of 6 m with a ratio of L/h = 22. The basic size of the beam length is 350 cm with a cross-section of 2×80×80 mm. The ties in the beams are installed in three ways:

a) with a uniform step along the beam length;

b) with an uneven step according to the arcsine law in accordance with the Recommendations for the design and manufacture of wooden structures with connections on plates with cylindrical dowels (KirPI-TsNIISK systems);

c) with a minimum permissible step in the zone of the greatest shear stresses at the ends of the beam.

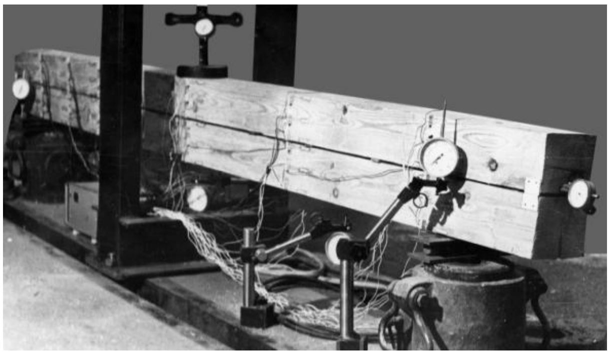
The main number of beams has an uneven arrangement of shear ties, as the most universal. The number of shear ties in the beams was determined in accordance with Code of Practice SP 64.13330.2017 "Wooden Structures" (issued by the Ministry of Construction and Housing and Communal Services of the Russian Federation) with a coefficient of Kt = 1.0 and amounted to n = 7 pcs per half-length of the beam. The transverse load on the beams was applied in three types according to Fig. 3.

The timber of the beams corresponds on average to grade 2 according to Interstate standard GOST 8486–86 "Softwood lumber. Technical conditions" with an average elastic modulus in bending E_b = 10590 MPa and elastic modulus of the timber at the location of the strain gauges E_w = 11570 MPa, the humidity at the time of testing was 7–10 %. The results of short-term tests for the first loading are given in Table 3. The photos in Fig. 6 show the beams during testing.

Table 3. Test results of composite beams of series 1 and 3.

No.	$\frac{M_{norm}}{M_{cal}}$ (kN·cm)	Deflections (mm)		Shifts (mm)		Relative deformations (mm x 2·10^5)		M_{dest} (MPa)	K_{sat}
		f_{centre}	f_1	Δ_{sup}	Δ_1	ε_{up}	ε_{lov}		
B1.1	240.10 360.15	11.92 18.91	8.93 14.12	0.07 0.15	0.15 0.35	–152 –230	149 224	768.3	2.13
B1.2	240.10 360.15	11.10 18.87	7.99 13.72	0.08 0.22	0.05 0.20	–142 –241	161 270	802.4	2.23
B1.3	215.90 359.90	13.96 25.19	10.61 19.61	0.31 0.72	0.26 0.67	–126 –220	222 373	787.7	2.19
B1.4	216.00 360.00	12.73 23.98	9.70 18.54	0.42 0.95	0.25 0.55	–112 –208	94 166	570.0*	–
B1.5	216.00 360.00	11.60 21.98	9.24 16.64	0.13 0.44	0.09 0.31	–123 –210	120 200	819.0*	2.28
B3.1	240.10 360.15	9.09 15.81	6.80 11.85	0.18 0.47	0.21 0.51	–117 –181	104 171	1426.3	3.96
B3.2	240.10 360.15	10.41 17.38	7.75 13.00	0.21 0.47	0.25 0.54	–141 –217	107 163	1248.6	3.47
B3.3	240.10 360.15	10.41 18.15	7.67 13.30	0.17 0.43	0.22 0.48	–111 –181	121 200	1156.4	3.24
B3.4	215.90 359.90	10.50 20.12	8.16 15.74	0.14 0.47	0.20 0.55	–99 –168	117 191	1131.7	3.14
B3.5	189.00 315.00	9.03 16.10	7.40 13.59	0.32 0.78	0.13 0.34	–94 –160	103 173	905.6	2.87

* not subject to destruction



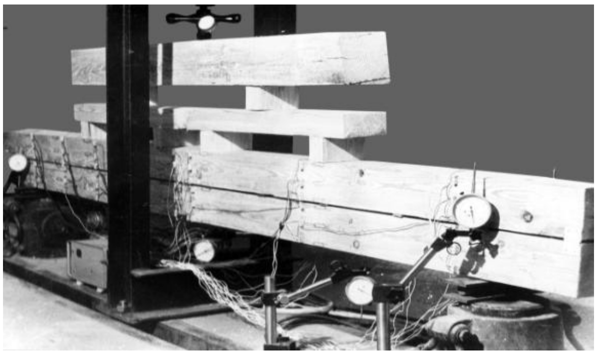


Figure 6. Beams during testing.

The destruction of the beams in the target experiment occurred mainly due to the rupture of fibers in the zone of action of the maximum bending moment in the stretched part of the beam cross-section. Longitudinal chipping of wood was also observed (chipping along the cross-grain or knot zone and chipping along the area of action of tangential stresses with subsequent rupture of wood fibers). The destruction occurred in a rather wide range of applied forces, the safety factor K_{sat} fluctuated within 2.13...3.95. The lower limit of the factor is due to the large ratio L/h of the beams, which leads to a decrease in the bending strength of the wood.

After testing the beams, each beam was calculated for the design load using the method developed in [28] with previously determined rigidity characteristics of the shear ties [27]. Table 4 provides a summary of the experimental and theoretical values of deflections f, edge stresses $\sigma_{up(low)}$ and shears along the bonding seam Δ for all beams in the target experiment.

Table 4. Comparison of calculation results with test data of composite beams of series 1 and 3.

	No.	Experiment				Calculation α_t = 0				Calculation α_t = 0.85 cm			
		f (mm)	Δ (mm)	σ_{up} (MPa)	σ_{lov} (MPa)	f (mm)	Δ (mm)	σ_{up} (MPa)	σ_{lov} (MPa)	f (mm)	Δ (mm)	σ_{up} (MPa)	σ_{lov} (MPa)
Series 1	B1.1	18.9	0.55	12.4	10.4	17.0	0.53	12.4	12.6	21.5	0.55	14.4	14.6
	B1.2	18.8	0.42	13.3	13.5	15.4	0.47	13.5	13.5	19.6	0.49	15.3	15.3
	B1.3	25.1	0.66	12.2	14.1	19.3	0.67	11.6	11.7	24.9	0.69	13.8	13.9
	B1.4	24.2	0.95	10.1	12.8	22.5	1.06	10.0	11.6	27.1	1.04	12.3	14.5
	B1.5	21.5	0.84	12.2	11.3	20.3	0.83	11.4	11.3	25.8	0.87	13.9	13.9
Series 3	B3.1	15.8	0.46	11.5	9.6	12.9	0.41	12.0	12.1	15.9	0.42	13.8	13.9
	B3.2	17.3	0.47	14.6	13.4	14.5	0.47	11.8	11.8	18.4	0.49	13.6	13.6
	B3.3	18.1	0.43	12.0	12.6	14.8	0.44	13.9	14.1	18.8	0.46	15.9	16.1
	B3.4	20.1	0.57	10.3	10.6	17.1	0.60	11.9	11.6	21.9	0.61	14.1	13.8
	B3.5	16.1	0.78	10.5	9.0	14.8	0.76	9.14	9.38	18.8	0.73	11.2	11.4

The difference in the indicated values between the theoretical and experimental values is generally small. On average, the experimental values are between the calculated values when calculating with α_t = 0 and α_t = 0.85 cm.

For beams loaded with a concentrated force in the middle of the span and four forces along the span, the closest theoretical value of deflections is α_t = 0,85 cm and exceeds the experimental values by 1–9 %. For beams loaded with concentrated forces at the supports, the closest theoretical values are deflections α_t = 0, which are less than the experimental values by 5.5–7.5 %. This is due to a decrease in the value of α_t when loaded with concentrated forces at the beam supports. In general, the difference between experimental and theoretical deflection values is on average 11 %, which quite convincingly confirms the validity of theoretical calculations.

A good convergence of the results is obtained for shears along the bonding seam. For edge stresses, the convergence of the results is somewhat worse, the maximum discrepancy reaches 39 %, although in the direction of increasing theoretical values, and the difference on average is 1.8–16 %. This is due to the relative accuracy of determining the elastic modulus of wood at the location of the resistance strain gauges E_w based on the internal moment in the beam section, compared to previously used methods.

4. Conclusion

As a result of the experimental and theoretical study of composite beams from two bars connected by TGk dowel plates under short-term loading, the nature of the beams' operation was established depending on the type of force action and the method of arranging shear ties.

An experimental verification of the calculation method for composite wooden bending rods with discrete shear ties was performed.

In general, the difference between the experimental and theoretical values of beam deflections is less than 20 %, which quite convincingly confirms the validity of theoretical calculations.

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