Magazine of Civil Engineering

ISSN 2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 692.526

DOI: 10.34910/MCE.120.4

Behavior of timber-timber composite structure connected by inclined screws

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Keywords: stress-strain state, cross laminated timber (CLT), glulam (GLT), bending tests, timber-timber composite (TTC), dowels, inclined screws, strength, stiffness, finite element method, numerical model

Abstract. The behavior of timber composite structure made of cross laminated timber (CLT) panel and glued laminated timber (GLT) beam was considered in this paper. Bending tests of a CLT-GLT composite structures with and without fasteners were conducted. CLT panel and GLT beam were connected by screws installed at a 45° angle to the GLT axis grain. It was experimentally proved that the application of inclined screws increases the strength of the CLT-GLT composite structure by 1.3 and 1.6 times, stiffness – by 1.6 and 2.1 times, shear capacity – by 2.1 and 3.5 times for two orientation types of CLT panel (CI and CII), respectively. Two types of CLT panel orientations were considered: with the top layer oriented parallel to the GLT axis (CI) and oriented perpendicular to the GLT axis (CII). The CLT-GLT composite structure with the top layer oriented parallel to the axis of the GLT beam has 50 % more strength and 14 % more stiffness than a composite structure with the top layer oriented perpendicular to the GLT axis. Based on numerical and experimental results, a design procedure was suggested to determine the strength and strain characteristics of the CLT-GLT composite structure connected by inclined screws.

Funding: The authors acknowledge the financial support given to this study by the Foundation for Assistance to Small Innovative Enterprises, the program “U. M. N. I. K.” (contract No. 14123GU/2019 dated 10.06.2019).

Acknowledgements: The authors also gratefully acknowledge the support given to this study by LLC Promstroyles.

Citation: Chernova, T.P., Melekhov, V.I. Behavior of timber-timber composite structure connected by inclined screws. Magazine of Civil Engineering. 2023. 120(4). Article no. 12004. DOI: 10.34910/MCE.120.4

1. *Introduction*

The successful development of engineered wood products (such as CLT, LVL, OSB, etc.), nowadays a building materials of global interest, offered further favorable opportunities for copious application of construction wood. One of the directions for the application of engineered wood products is the research of new design solutions for CLT composite structures.

In the composite structures the CLT panel is connected with GLT beam in forms of a ribbed or box-shaped cross-section, supported by metal beams or profiled sheeting, formed into a timber-concrete composite structure, i.e. timber composite systems (Fig. 1, a-d).

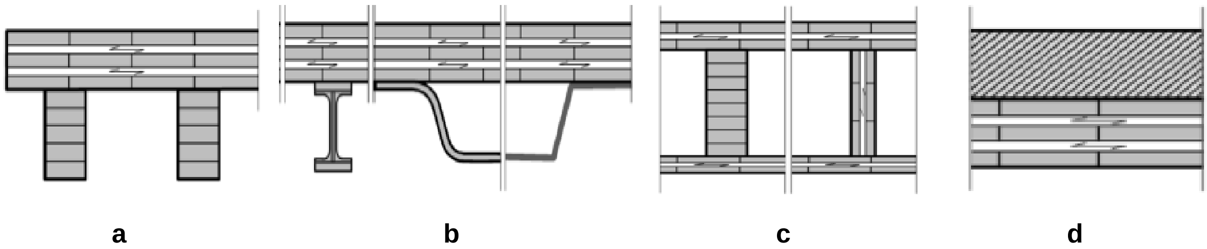


Figure 1. Timber composite systems [1]: a – ribbed cross-section of the CLT-GLT structure; b – CLT with metal beams; c – box-shaped cross-section of the CLT-GLT structure; d – composite cross-section of CLT-concrete.

CLT panels formed into steel-timber composite (STC) were considered by [2, 3], etc.; timber-concrete composite (TCC) – by [4–9], etc.; timber-timber composite (TTC) – by [10–24], etc.

The research results of timber composite structures connected by screws were given in the papers of J.M. Branco [11], A.A. Chiniforush [12], I. Giongo [14, 15], R. Masoudnia [18–21], D. Riccadonna [22], G. Schiro [23], etc.; by glued perforated steel plates – in the paper of J. Estévez-Cimadevila [13], etc.; by punched metal plates – in the papers of N. Jacquier [16, 17], etc.; by glue – in the papers of S. Aicher [10], I. Sustersic [24], etc.

The studies of R. Masoudnia et al. [18–21] present the effect of the panel and beam configuration on the effective flange width of timber composite beam. Research of J.M. Branco et al. [11] confirms the increase in strength and stiffness characteristics of TTC connections with screws installed at an angle of 45° to the grain of wood, compared with TTC connections with screws installed perpendicular to the grain of wood.

The issues of composite action between elements and reinforcement of timber composite structures by dowel fasteners installed at an angle to the grain of wood were investigated by [25–31], etc.

The research results of reinforcement of timber composite structures by screws were given in the papers [25–27]; by glued-in steel rods – in papers [28, 29]; by screws with anchorage details – in paper [30]; by twisted cruciform rods – in paper [31].

The models for predicting the behavior of the composite structures can be classified into three groups: numerical, empirical, and analytical.

Nowadays, numerical methods are widely used. In particular, finite element models are the most common way to analyze composite structures. Unfortunately, a finite element model of a composite structure that has not been checked against analytical results or experimental data does not guarantee high reliability, since many factors impinge on a numerical solution. The most precise design method for composite structures is an experimental one, but it is characterized by increased workability. Therefore, analytical methods, which are the most general and economical, are used. There are several analytical design procedures for composite structures [32], including mechanically jointed beams theory (gamma method), composite theory (k-method) [33], shear analogy method and transformed section method. In addition, other methods [34–36] are used for the designing of composite structures subjected to flexure. None of the above mentioned analytical design procedures has been universally accepted yet.

The aim of the study was to verify the suggested design procedure for determining the strength and strain characteristics of a composite structure made of CLT panel and GLT beam connected by inclined screws.

Study objectives:

- to determine the strength and strain characteristics of a composite structure made of CLT panel and GLT beam connected by inclined screws;
- to compare the results obtained by the suggested design procedure, the numerical and experimental results for a composite structure made of CLT panel and GLT beam connected by inclined screws.

2. Methods

The research program includes numerical, analytical and experimental analyses of the strength and strain characteristics of a timber-timber composite structure.

Numerical analysis of the strength and strain characteristics of composite structures made of CLT panel and GLT beam connected by inclined screws, without fasteners and the CLT-GLT solid structure with rigid connection was carried out.

Numerical analysis of the behavior of the CLT-GLT composite structure was conducted using the ANSYS software (Fig. 2), taking into account the anisotropic properties of wood (Orthotropic Elasticity) for the GLT beam and the layers of the CLT panel. Solid elements (SOLID 186) were used for the numerical analyses. Boundary conditions were applied to the numerical model of timber composite structure by constraining the necessary nodes to represent the simply-supported condition. The CLT-GLT composite structures with a span of 3,000 mm were loaded according to a 2-point scheme for each GLT beam. A contact region between the layers of the CLT panel was modeled using “bonded” configuration. Contact regions between CLT panel and GLT beam were applied using different configurations: “no separation” for the CLT-GLT composite structures connected by inclined screws and without fasteners, “bonded” for the CLT-GLT solid structure with rigid connection.

Figure 2. Numerical model of CLT-GLT composite structure.

The coefficients k_W and k_{EI} were obtained from numerical analysis:

$$k_W = \frac{\sigma^{solid}}{\sigma^{composite}}, \; k_{EI} = \frac{w^{solid}}{w^{composite}} \tag{1}$$

where σ^{solid}, w^{solid} are normal stress and mid-span deflection of the CLT-GLT solid structure with rigid connection; $\sigma^{composite}$, $w^{composite}$ are normal stress and mid-span deflection of the CLT-GLT composite structure.

The suggested design procedure for determining the strength and strain characteristics of a composite structure made of CLT panel and GLT beam connected by inclined screws includes:

- calculation of normal stresses and mid-span deflection of the CLT-GLT solid structure with rigid connection;
- application of coefficients k_W and k_{EI} for calculation of normal stresses and mid-span deflection of a composite structure made of CLT panel and GLT beam connected by inclined screws.

Normal stresses σ and mid-span deflection w of the CLT-GLT solid structure loaded according to a 2-point scheme can be determined by the equations:

$$\sigma = \frac{M}{W_{red} \cdot k_W} \le R \cdot m, \; w = \frac{N \cdot l^3}{24 \cdot E \cdot I_{red} \cdot k_{EI}} \cdot \left(3\frac{a}{l} - 4\frac{a^3}{l^3}\right) \tag{2}$$

where M is a bending moment; W_{red} is a section modulus of the cross-section of a structure relative to its own neutral axis; R is a design resistance taking into account a coefficient m; N is a magnitude of concentrated load; l is a span of the structure; a is a distance between support and concentrated load; E is a modulus of elasticity of the GLT beam in longitudinal direction; I_{red} is the second moment of area of the structure relative to its own neutral axis; k_W, k_{EI} are coefficients (k_W = 1, k_{EI} = 1 for the CLT-GLT solid structure with rigid connection).

Section modulus of the cross-section of the CLT-GLT solid structure with rigid connection relative to its own neutral axis can be determined by equation (3):

$$W_{red} = \frac{I_{red}}{e} = \frac{\sum_{i=1}^{n} I_i + \sum_{i=1}^{n} A_i \cdot e_i^2}{e} \tag{3}$$

where A_i is cross-sectional area of separate element (layer or GLT beam); I_i is second moment of area of separate element (layer or GLT beam) relative to its own main axis; e_i is distance from the neutral axis of the whole structure to the neutral axis of separate element (layer or GLT beam); e is distance from the neutral axis of the whole structure to the point on the cross section of the structure at which the normal stress is to be determined.

The following simplifications must be taken into account during the design procedure for determining the strength and strain characteristics of a composite structure made of CLT panel and GLT beam connected by inclined screws:

- cross-sectional area of the CLT panel layer must be determined using the reduction factor, which depends on the ratio of modulus of elasticity of the layer and GLT beam;
- coefficients k_W and k_{EI} depend on geometrical parameters and strength characteristics of connection;
- modulus of elasticity of CLT panel in transverse direction can not be taken into account.

Experimental analysis of two groups of CLT-GLT composite specimens was carried out.

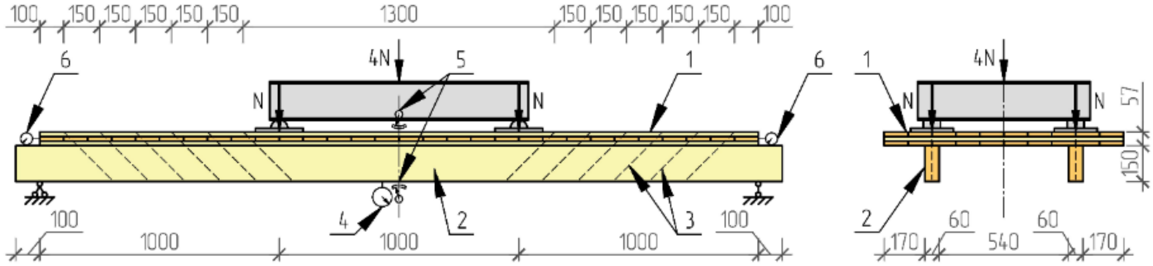
The first group included four CLT-GLT composite specimens without fasteners where CLT panel was simply-supported by GLT beam. Two variants of the CLT panel's orientation were considered: with the top layer of the panel oriented parallel to the GLT axis (CI) and oriented perpendicular to the GLT axis (CII). Nondestructive tests of the first group specimens were conducted during elastic stage. The tested specimens were used later to second group of CLT-GLT composite specimens.

The second group included four CLT-GLT composite specimens, which were prepared with compliant joint provided by inclined screws SPAX with length and diameter equal to 300 and 8 mm, respectively. The screws were placed under the angle of 45° relatively to longitudinal axis of the specimens. The screw spacing was taken as 150 mm. Two variants of the CLT panel's orientation (CI and CII) were considered. Tests of the second group were conducted until failure.

The characteristics of the materials used in the experimental tests were as follows:

- GLT beams with a strength class of GL20h were formed into cross-section of 150×60 mm (3 parts with a cross-section of 50×60 mm). The moduli of elasticity of the spruce GLT beams (9,465 MPa in longitudinal direction, 410 MPa in transverse direction) were experimentally determined;
- CLT panels with a strength class of C14 were 57 mm thick and were composed of three layers of 19 mm. The moduli of elasticity of the spruce CLT longitudinal boards (7,000 MPa in longitudinal direction, 230 MPa in transverse direction) were defined from technical approval;
- SPAX screws were made of carbon steel with characteristics from European Technical Approval ETA-12/0114.

The simply supported composite structure with the span of 3,000 mm was tested in a 4-point bending setup (Fig. 3). The loading scheme was selected so that the shear forces in the connection of timber composite structure were most fully manifested. The CLT-GLT composite structure was loaded by a jack with a developing load of 200 kN. The loading was applied to the structure through a steel distribution beams. Steel plates 20 mm thick were installed on the supports and under the distribution beams to avoid compression perpendicular to the grain of the wood. The tests were conducted at the temperature of 20–24 °C and relative humidity of 50–60 %.



a b

c

Figure 3. Test setup: a – longitudinal section; b – cross-section; c – general view; 1 – CLT panel; 2 – GLT beam; 3 – screws; 4 – flexometer; 5 – strain gauges; 6 – displacement transducers.

The mid-span deflections of the structures were measured by flexometers. Measurements of wood grain strain were obtained using strain gauges installed at the compressed surface of the CLT panel and the tensile surfaces of the GLT beams. Slips between the CLT panel and the GLT beams were determined using displacement transducers installed at the edges of the CLT panel.

The sequence of the experiments:

1. Bending tests of composite structures by loading in stages of 1.4 kN at intervals of 5 minutes until failure. The mid-span deflections, slips between the CLT panel and the GLT beams, wood grain strain at each loading step are recorded and the destructive load $N_{\max}$ is determined.

2. Graphic documenting and analysis of the failure mode of the CLT-GLT composite structures.

3. Drawing of mid-span normal stresses distributions along cross-sectional depth of composite structures, load-deflection and load-slip curves.

4. Calculation of reliability coefficient for brittle failure of timber in accordance with the requirements of Interstate Standard GOST 33082-2014:

$$\gamma_{\nu} = 1.64 \cdot \left(1.94 - 0.116 \cdot \lg t\right), \tag{4}$$

where $t = t_{\max}/38.2$ is loading time to failure adjusted to a constant destructive load $N_{\max}$, sec; $t_{\max} = n^2 \cdot t_n$ is test time, sec; n is number of load stages; t_n is stage time, sec.

5. Calculated load-carrying capacity of the CLT-GLT composite structure:

$$R_{\exp\nu} = N_{\max}/\gamma_{\nu}. \tag{5}$$

6. Comparison of the results obtained by the suggested design procedure, the numerical and experimental results for composite structure made of CLT panel and GLT beam connected by inclined screws.

3. Results and Discussion

The mid-span deflections and slips derived from the numerical analysis of the CLT-GLT composite structure were compared with the experimental deflections and slips (Table 1).

Table 1. Experimental and numerical results for timber composite structures.

Type of structure		At N = 3.5 kN				At N_{max} = 25.44 kN for CI At N_{max} = 16.97 kN for CII			
		Mid-span deflection, mm		Slip, mm		Mid-span deflection, mm		Slip, mm	
		Exp.	Num.	Exp.	Num.	Exp.	Num.	Exp.	Num.
Rigid connection	CI	–	4.90	–	0	–	35.65	–	0
	CII	–	6.19	–	0	–	30.03	–	0
With fasteners	CI	8.28	8.67	0.594	0.600	63.30	63.00	4.943	4.365
	CII	9.41	9.97	0.606	0.594	47.00	48.33	3.325	2.881
Without fasteners	CI	13.10	15.00	1.275	1.254	(95.24)	(109.08)	(9.269)	(9.119)
	CII	19.63	21.29	2.114	2.191	(95.15)	(103.22)	(10.248)	(10.624)

Fig. 4 shows the load-deflection and load-slip curves for CI and CII composite structures made of CLT panel and GLT beam connected by inclined screws (B+P+S), without fasteners (B+P+0) and the CLT-GLT solid structure with rigid connection (B+P).

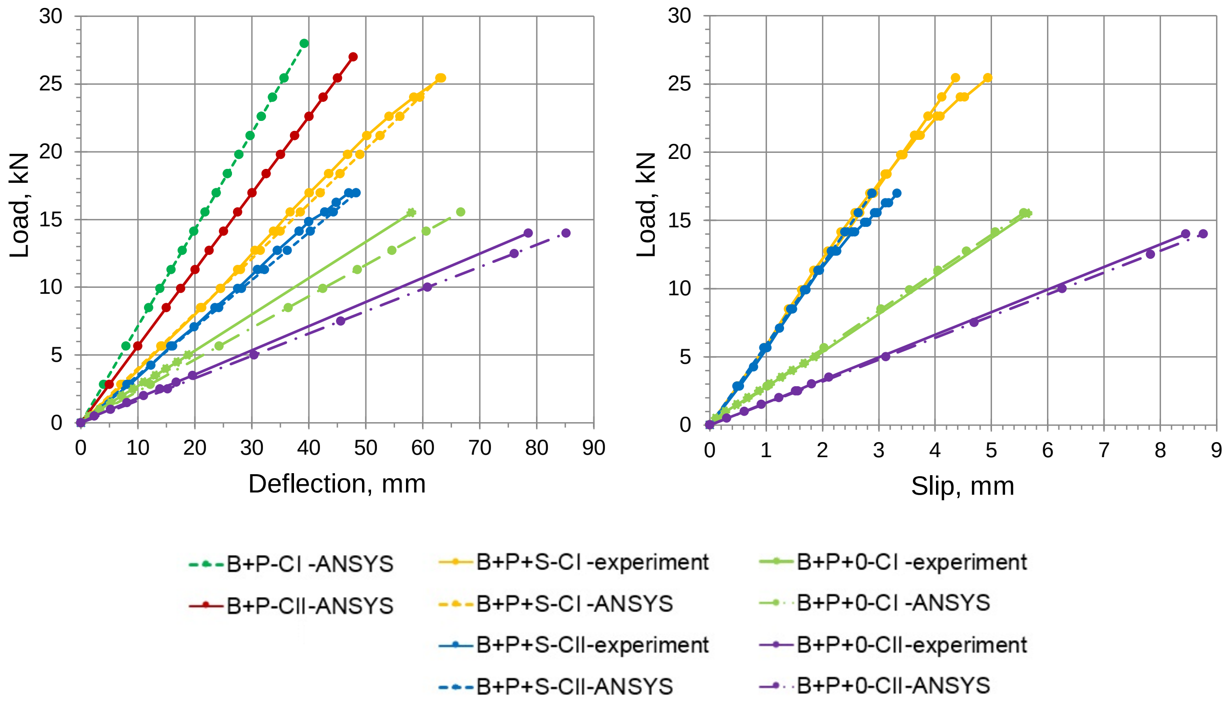


Figure 4. Load-deflection and load-slip curves for the CLT-GLT composite structures bending tests.

As a result of the stress-strain characteristics studies carried out for the CLT-GLT composite structure, it can be noted:

– the CI composite structure has 50 % more strength and 14 % more stiffness than the CII composite structure;

– the application of inclined screws increases the strength of the CLT-GLT composite structure by 1.3 and 1.6 times, the stiffness by 1.6 and 2.1 times, and the shear capacity by 2.1 and 3.5 times for CI and CII, respectively.

Fig. 5 shows the mid-span normal stresses distributions along cross-sectional depth of CI and CII composite structures (MPa) obtained by numerical and experimental analyses. The experimental values are shown in brackets.

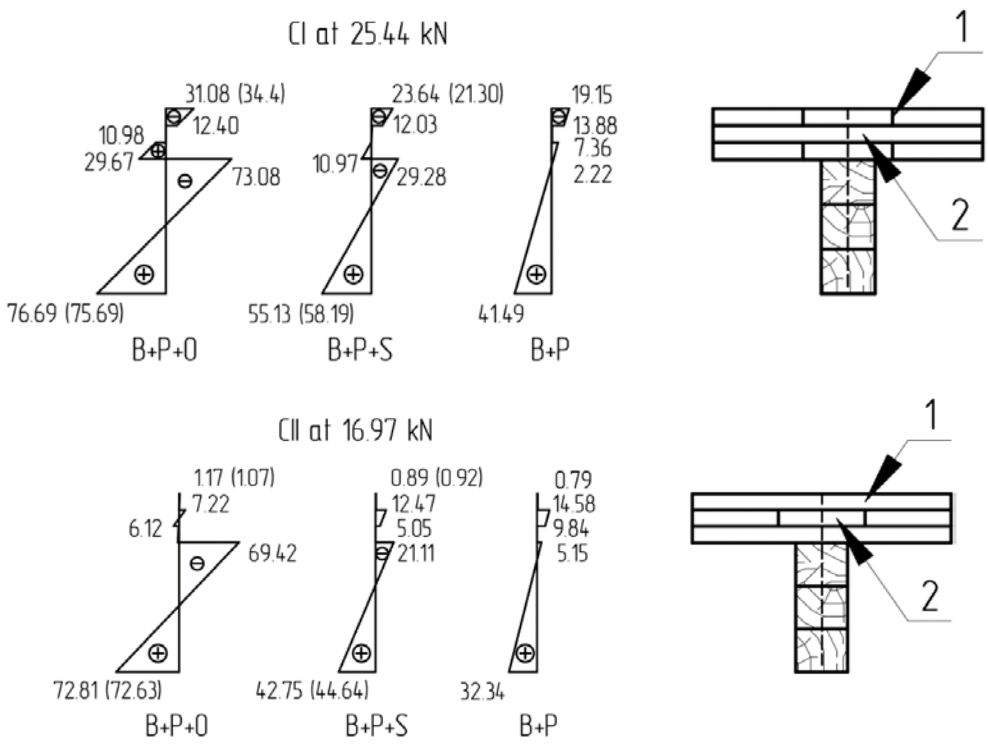


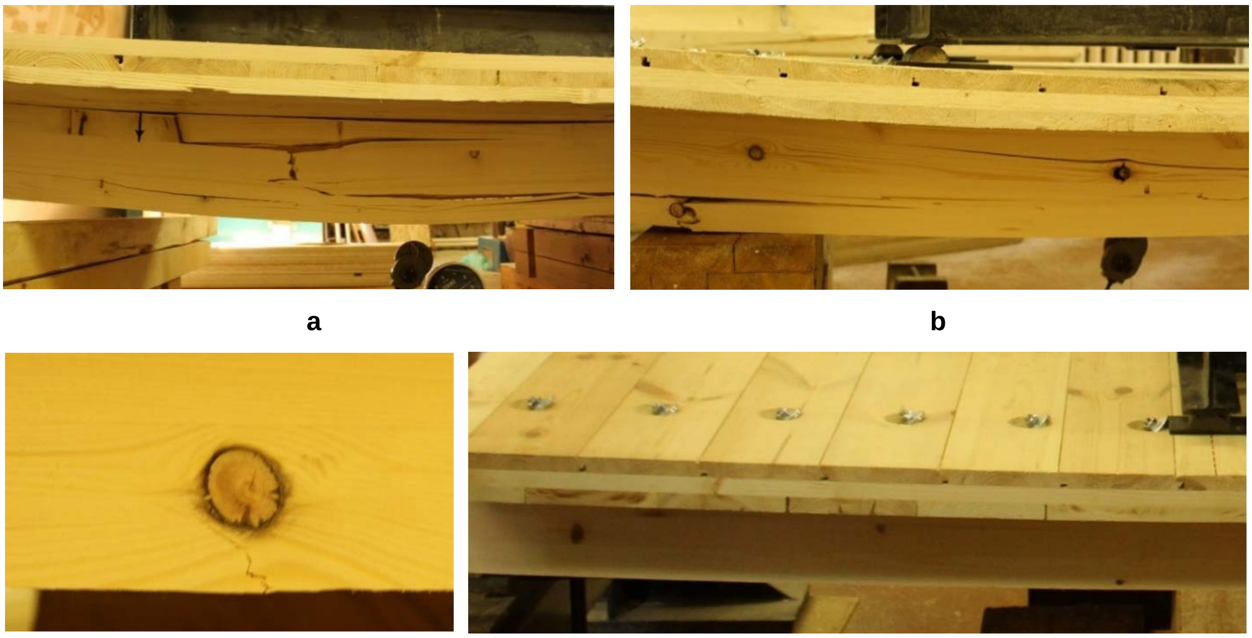
Figure 5. Mid-span normal stresses distributions along cross-sectional depth of CI and CII composite structures: 1 – top layer of CLT panel; 2 – cross layer of CLT panel.

When bending tests of CI and CII composite structures connected by inclined screws, brittle failure of the GLT beams in the middle of the span caused by normal tensile stresses was observed (Fig. 6, a-d).

The failure of the CI composite structure occurred in the tensile zone of the GLT beam with subsequent cracking along the plane perpendicular to the longitudinal axis of the beam.

The failure of the CII composite structure occurred in the tensile zone of the GLT beam. The crack developed from a knot along the plane inclined to the longitudinal axis of the beam. During loading, a gap developed between the lamellas of the bottom CLT layer.

The brittle failure of GLT beams in the middle of the span caused by bending tensile stresses corresponds to the results of studies in the publications [12–15].



a b

c d

Figure 6. Failure of the CLT-GLT composite structures: a – CI; b – CII; c – knot in the tensile zone of the GLT beam (CII); d – gap between lamellas of the CLT panel.

A comparison of the results obtained by the suggested design procedure, the numerical and experimental results for the CLT-GLT composite structures is provided in Table 2.

Table 2. Comparison of experimental and numerical results for the CLT-GLT composite structures.

Method	Numerical analysis (1)		Design procedure (2), (3)		Experimental analysis	
	CI	CII	CI	CII	CI	CII
Destructive load $N_{\max}$, kN	–	–	–	–	25.44	16.97
Reliability coefficient, γ_v	–	–	–	–	2.81	2.88
Load-carrying capacity R_{expv}, kN	8.31	5.36	8.51	5.98	9.04	5.89
Differences between load-carrying capacity, %	**8.10**	**9.00**	**5.90**	**1.48**	**–**	**–**
Mid-span deflection of composite structure $w^{composite}$, mm	63.00	48.33	56.57	47.16	63.30	47.00
Differences between mid-span deflection, %	**0.47**	**2.75**	**10.64**	**0.33**	**–**	**–**
Mid-span deflection of solid structure w^{solid}, mm	35.65	30.03	32.01	29.3	–	–
Coefficient k_{EI}	0.57	0.62	0.57	0.62	–	–
Normal stresses of composite structure $\sigma_{c,CLT}^{composite}$, MPa	–23.64	–0.89	–26.63	0.00	–21.30	–0.92
Normal stresses of composite structure $\sigma_{t,GLT}^{composite}$, MPa	55.13	42.75	57.43	45.43	58.19	44.64
Differences between normal stress in tensile zone, %	**5.26**	**4.42**	**1.31**	**1.75**	**–**	**–**
Normal stresses of solid structure $\sigma_{c,CLT}^{solid}$, MPa	-19.15	-0.79	-21.57	0	–	–
Normal stresses of solid structure $\sigma_{t,GLT}^{solid}$, MPa	41.49	32.34	43.22	34.37	–	–
Coefficient k_W for $\sigma_{c,CLT}$	0.81	0.89	0.81	0.89	–	–
Coefficient k_W for $\sigma_{t,GLT}$	0.75	0.76	0.75	0.76	–	–
Slip υ, mm	4.365	2.881	–	–	4.943	3.325
Differences between slip, %	**11.69**	**13.35**	–	–	–	–

Table 2 presents determining of a coefficients k_W and k_{EI} from numerical analysis, calculation of normal stresses and mid-span deflection of the CLT-GLT solid structure with rigid connection and application of coefficients k_W and k_{EI} for calculation of normal stresses and mid-span deflection of a composite structure made of CLT panel and GLT beam connected by inclined screws.

For the CI (CII) composite structure connected by inclined screws the differences between numerical and experimental results are as follows:

- load-carrying capacity is 8.1 % (9.0 %);
- mid-span deflection is 0.47 % (2.75 %);
- normal stress in tensile zone is 5.26 % (4.42 %);
- slip between the CLT panel and the GLT beam is 11.69 % (13.35 %).

The differences between the slips obtained by numerical and experimental analyses can be explained by determining slips between the CLT panel and the GLT beam in the elastic stage of numerical modeling.

For the CI (CII) composite structure connected by inclined screws the differences between the results obtained by the suggested design procedure and experimental tests are as follows:

- load-carrying capacity is 5.9 % (1.48 %);
- mid-span deflection is 10.64 % (0.33 %);
- normal stress in tensile zone is 1.31 % (1.75 %).

The close agreement between results obtained by design procedure, the numerical and experimental results confirmed that the suggested design procedure is sufficiently accurate for determining strength and strain characteristic of a composite structure made of CLT panel and GLT beam connected by inclined screws.

4. Conclusions

1. A numerical model for determining the strength and strain characteristics of a composite structure made of CLT panel and GLT beam connected by inclined screws was developed. The accuracy of the proposed numerical model of timber composite structure was verified. The maximum differences between the load-carrying capacity, mid-span deflection, normal stress in tensile zone and slip between CLT panel and GLT beam calculated using numerical model and experimentally were equal to 9.0 %, 2.75 %, 5.26 % and 13.35 %, respectively.

2. A design procedure for determining the strength and strain characteristics of a composite structure made of CLT panel and GLT beam was suggested. The suggested engineering method for the CLT-GLT composite structure was verified. The maximum differences between the load-carrying capacity, mid-span deflection and normal stress in tensile zone of the CLT-GLT composite structure obtained by the suggested design procedure and experimental tests were equal to 5.9 %, 10.64 % and 1.75 %, respectively

3. It was experimentally proved that the application of inclined screws increases the strength of the CLT-GLT composite structures by 1.3 and 1.6 times, stiffness – by 1.6 and 2.1 times, and shear capacity – by 2.1 and 3.5 times for CI and CII, respectively.

4. The CLT-GLT composite structure with the top layer oriented parallel to the axis of the GLT beam has 50 % more strength and 14 % more stiffness than composite structure with the top layer oriented perpendicular to the GLT axis.

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Received 18.01.2023. Approved after reviewing 06.04.2023. Accepted 03.05.2023.