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GLUED LAMINATED TIMBER BEAM REINFORCED WITH COMPOSITE STRIPS

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The technology of reinforcement, the methodology for determining the stress-strain state, and the calculation method for glued laminated timber beams reinforced with composite strips have been proposed. Results of deformation parameters of the experimental model, actual bending modules of elasticity, maximum longitudinal stresses at the mid-span, at the load application axis, and at the support axis are presented. The actual maximum load-bearing capacity of the experimental model reinforced with composite strips has been determined. A comparison with numerical studies performed in a modern software package is also provided.

Keywords: composite strips, deformations, electrostrain measurement, glued laminated timber, glued timber structures, reinforcement of glued laminated timber, stress–strain state, stresses.

Introduction

Modern construction increasingly demands materials that are environmentally friendly and have minimal negative impact on the environment. At the same time, such materials must possess high strength and durability against various external influences. Timber structures, made from renewable natural resources and characterized by relatively high strength, meet these requirements and are thus considered sustainable materials [1-2, 22-35]. Although wood has certain disadvantages, such as shrinkage, decay and anisotropy of properties, these issues are more controllable in glued laminated timber (GLT) structures. Beams, as key elements of GLT, can significantly improve their stiffness and strength through reinforcement with composite materials.

To determine the stress–strain state (SSS) of glued laminated timber beams reinforced with composite strips under experimental conditions, the method of electrostrain measurement was used, along with individual measurements of vertical deformations using a dial gauge indicator.

To determine the SSS of glued laminated timber beams reinforced with composite strips using a numerical method, the LIRA 2024 software suite was applied.

The technology for reinforcing glued laminated timber beams with composite strips is presented.

It is confirmed that the proposed methods for determining the SSS of glued laminated timber beams reinforced with composite strips are appropriate for use in the design of both individual elements and complex systems based on them. Specifically, the reinforcement of glued laminated timber beams with composite strips proves to be an effective method for increasing the load-bearing capacity and stiffness of such structures.

Literature review

Despite the fact that solid wood has certain negative properties, namely susceptibility to shrinkage and swelling, decay, and anisotropy of properties - which require special attention in construction—these drawbacks are better controlled in glued laminated timber (GLT) structures. There are some limitations in the use of GLT structures, such as a restricted construction height, which makes the use of such structures with relatively large cross-sectional heights impractical. Therefore, research on reinforced GLT structures is gaining importance to increase load-bearing capacity and stiffness while reducing their cross-sectional dimensions.

One of the earliest structural solutions was a significant reduction of the rectangular cross-section of a wooden beam, achieved by means of a solid steel plate bent at the ends of the beam and fastened with dowels (see Fig. 1). Before fastening to the timber beam, the steel plate was tensioned to achieve a prestressing effect. Such composite beam structures (known as Tirbach system structures) first appeared in the early 20th century and are thoroughly described in [3].

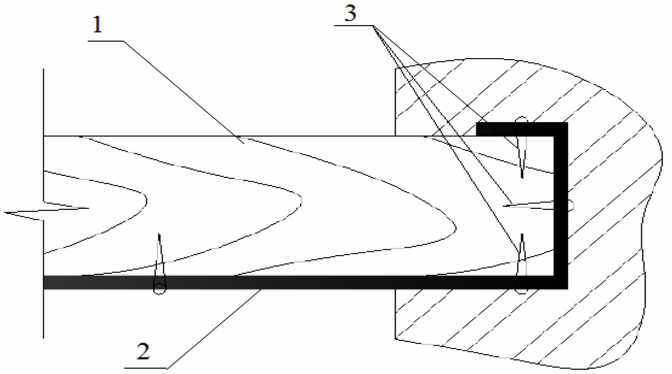


Fig. 1. Combined beam structures of the Tirbach system: 1 – wooden beam; 2 – steel plate; 3 – dowels

The further development of the idea to combine wooden load-bearing elements with metal was proposed in 1921 by L. Klaytile (USA) for use in the structures of airships and airplanes, employing box-section load-bearing elements with steel wire pressed into the flanges.

Over time, other variants of combining wood with metal were considered, such as embedding steel rods into pre-made grooves of a square wooden cross-section filled with special mastic, using steel strips with pre-made teeth for connection with wood, and employing reinforcing bars with ring-shaped protrusions at specific intervals designed to be pressed into specially made grooves for these protrusions. These methods were proposed by Fisher [4], A.D. Monchevich [5], and H. Granholm [4], respectively.

The effort to combine metal with wood led to the necessity of creating synthetic adhesives, which would simplify the connection of materials with different structures to wood, enabling the creation of efficient reinforced wooden structures.

Thus, from the late 20th century, the study of reinforced wooden structures began. Theories were considered stating that reinforcement increases the load-bearing capacity, stiffness, and reliability of wooden beams. The most effective reinforcement was in both the tensile and compressive zones (symmetrical reinforcement) (Fig. 2, a), or only in the tensile zone (single reinforcement) (Fig. 2, b). With a reinforcement ratio of 1–3%, the strength and stiffness increase by 1.4–3.2 times. The use of hot-rolled periodic-profile steel bars of classes A-II, A-III, and A-IV (A300C, A400C–A500C, A600C, respectively) is recommended. The reinforcement bars are placed into grooves, which are then filled with epoxy adhesive with filler, and the package is pressed.

Research on reinforced glued laminated timber structures is being conducted in Finland, Sweden, Germany, and the USA. The main advantages of reinforced beams are increased strength and stiffness, reduced cross-sectional height of the structures, and savings of up to 15% in high-quality timber. The disadvantages of such structures include increased labor intensity and manufacturing costs. Figure 3 shows the main reinforcement schemes of beams and their cross-sections.

The manufacturing technology of reinforced glued laminated timber structures differs from that of conventional glued laminated timber structures by the addition of an extra operation: bonding of reinforcing bars.

With the development of industry worldwide and the emergence of composite materials, the possibility has arisen over time to replace steel rolled reinforcement with lighter yet equally strong composite reinforcement.

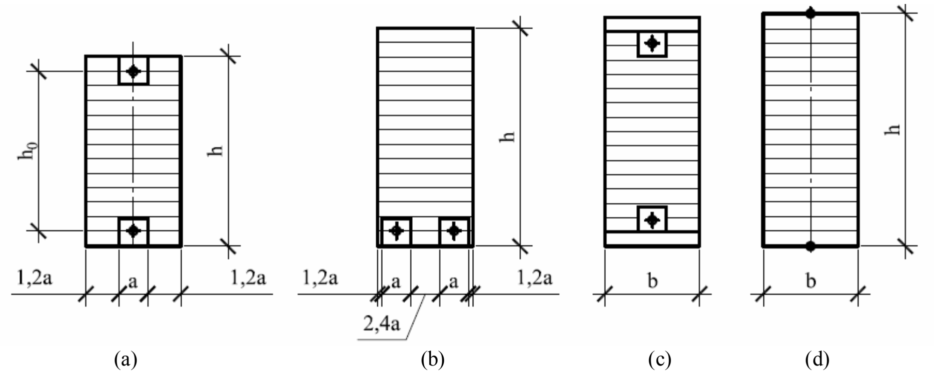


Fig. 2. Reinforcement of glued laminated timber beams:
(a) – cross-section of symmetric reinforcement; (b) – cross-section of asymmetric reinforcement;
(c) – beam with protective plates; (d) – arrangement of reinforcement for beam calculation

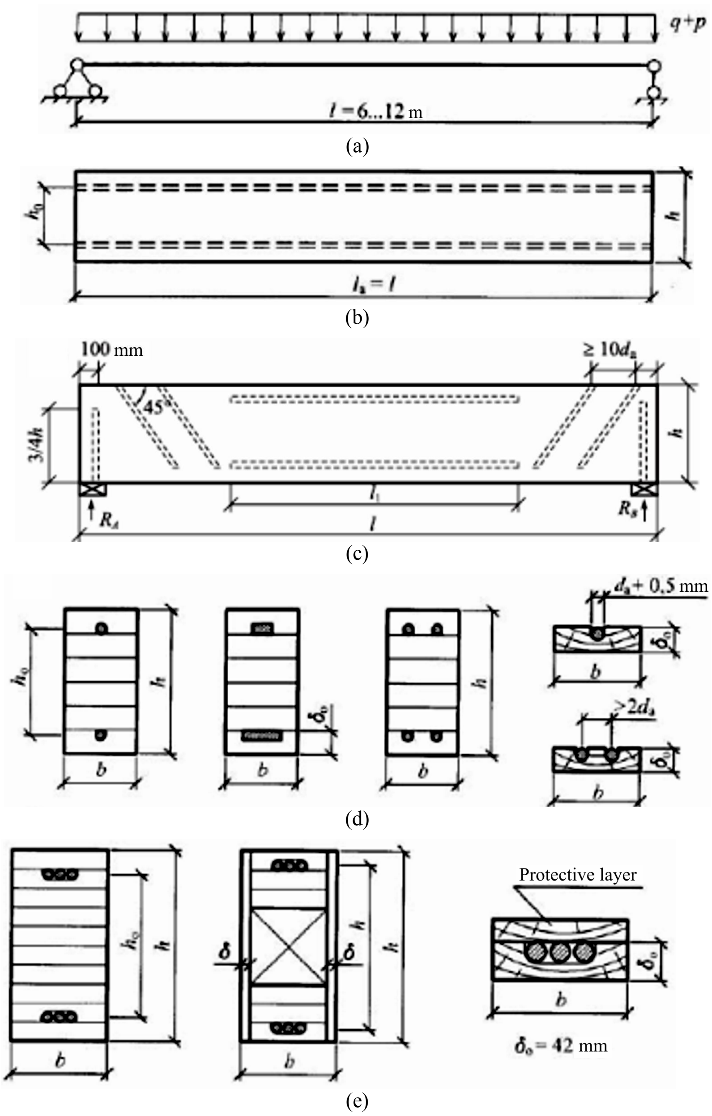


Fig. 3. Reinforcement of a glued laminated timber beam:
(a) – load application scheme; (b) – reinforcement scheme of the beam with single rods; (c) – beam reinforcement scheme;
(d) – types of cross-sections with single reinforcement; (e) – types of cross-sections with group reinforcement

In Ukraine, experience in designing glued laminated timber structures with rectangular cross-sections reinforced with composite strips is extremely limited. Most studies on such reinforcement focus on reinforced concrete structures [6–8]. In the work by S. Homon and M. Polishchuk [9], the technology for manufacturing glued laminated wooden beams reinforced with bar reinforcement and composite strips is experimentally investigated. The article by O. Bashynsky, T. Bondarchuk, and M. Peleshko [10] describes some experimental results including three methods of reinforcing wooden beams with strip reinforcement, which practically doubled their load-bearing capacity. Studies [11, 12] present numerical analysis results on the use of composite strips for strengthening various structures made of solid and glued laminated timber.

It is important to note that the latest versions of European Union standards (such as Eurocode 5 or EN 1995-1-1:2008 [13]) and Ukrainian standards (DBN V.2.6-161:2017 [14]) lack methodological recommendations for the design and calculation of glued laminated timber structures reinforced with composite strips.

The presented data confirm the need and effectiveness of conducting similar research on the reinforcement of glued laminated timber structures.

Aim and Objectives of the Research

The aim of this work is to present algorithms for reinforcing glued laminated timber beams with composite strips, to compare the results of experimental studies with numerical analysis of the stress-strain state, and to present a calculation method for glued laminated timber beams strengthened with composite strips based on two groups of limit states.

The object of the study is a glued laminated timber beam with an overall cross-section of $h_b \times b_b$ = 24×10 cm, consisting of 8 layers of boards with thickness t = 3 cm, beam length L = 400 cm, and effective span L_p = 375 cm. Pine wood of grade 3, grown in the Rivne region of Ukraine, was used to manufacture the tested beam.

In the tensile zone of the tested beam, carbon fiber composite strips Sika CarboDur S 512 with a cross-section of $h_a \times b_a$ = 0.12×5 cm were glued side-by-side across the entire width of the cross-section in accordance with technological requirements [15–18]. At a distance of 10 cm from the support axes, composite fabrics Sika Wrap – 230 C/45, 30 cm wide, were glued for anchoring the Sika CarboDur S 512 strips.

The tested beam rests on two hinged supports and is loaded with two concentrated forces located at ¼ and ¾ of the span length.

Composite Materials as a Modern Method of Reinforcement and Strengthening of Building Structures

The development of modern composite materials was primarily driven by the needs of shipbuilding, aviation, and space industries where they found wide application. One of the first modern composite materials was unidirectional fiberglass, consisting of artificial continuous glass fibers and a synthetic polymer matrix, invented by A.K. Burov and his colleagues in the 1930s. During the Great Patriotic War, fiberglass plates were used instead of aluminum in aircraft manufacturing.

In the 1960s, carbon fibers were developed in the United Kingdom, and boron fibers in the United States, which gave a push to the development of a new generation of composite materials that had a high modulus of elasticity, high strength, and stiffness, allowing the expansion of their application scope.

Most often, a composite material consists of two components — a continuous phase (matrix) and a filler. The matrix can be metallic, ceramic, or polymeric. The filler, in the form of fibers or particles, is usually made from strong and stiff materials (carbon, glass, aramid, polyethylene, steel, boron, carbide, silicon, etc.). Fibers in the matrix can be randomly oriented or have a certain orientation direction (Fig. 4).

Fiber-based composite materials, which are currently used for reinforcement, repair, and strengthening of building structures, are made from elongated microfibers embedded in a curing polymer, combining them into a single unit. Carbon, aramid, and glass fibers are the most common types of fibers. Epoxy and polyacrylonitrile resins are most frequently used as curing polymers.

Composite materials with carbon fibers are primarily used for reinforcement and strengthening of building structures. The most common forms of composite materials used for strengthening are fabrics of various weaves and strips or plates.

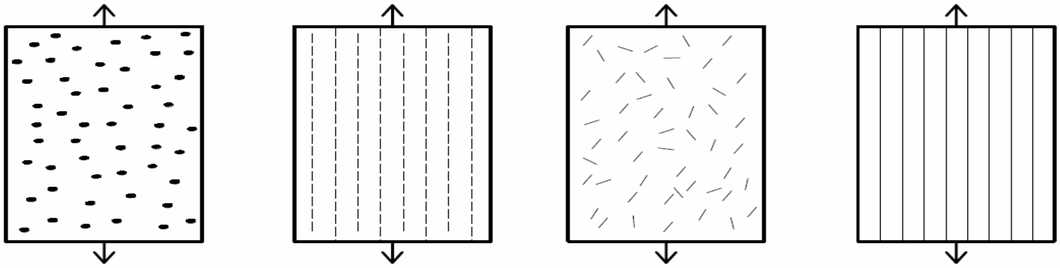


Fig. 4. Examples of composites: (a) – filled with randomly distributed particles; (b) – unidirectional short fibers; (c) – randomly oriented short fibers; (d) – unidirectional continuous fibers.

Fabrics are flexible textiles with unidirectional or bidirectional fiber orientation that, when applied to a structure, are impregnated with a polymer adhesive matrix, which ensures tight adhesion to the structure.

Strips or plates are factory-made composite products that are bonded to a pre-prepared surface of the structure.

The physico-mechanical properties of composite materials depend on the type and amount of fibers used, their distribution and orientation in the cross-section of the strip, as well as the volumetric ratio of fibers to the curing polymer in the composite.

The choice of composite material type for reinforcement or strengthening depends on the operating conditions and the purpose of the reinforced structures. The type of fibers to be used and their arrangement in the material (unidirectional or bidirectional) determine the strength and deformation characteristics of the composite fabric. In bidirectional arrangements, usually 70% of the fibers are oriented in the direction of the expected main external load, and 30% in the transverse direction. At the same time, the strength of such material in the main direction significantly decreases.

However, apart from the mechanical parameters of composite materials, which are directly necessary for calculating the load-bearing capacity of reinforced structures, many other physical parameters must be considered during design, which subsequently affect the performance of the repaired structure: resistance to chemical exposure and impact loading, long-term strength, fire resistance, electrical conductivity, compliance with sanitary and hygienic requirements, and others.

The reinforcement or strengthening system of structures with composite materials consists of two important components — the composite material itself and the adhesive or bonding agent. The successful functioning of such a system depends both on the reliability of each component and on the reliability of their joint operation. Besides bonding, the main purpose of the adhesive component is to resist shear and peeling forces between the bonded surfaces. Epoxy two-component adhesives, capable of curing at positive ambient temperatures, are most commonly used for bonding composite materials to surfaces.

Most adhesives are used for bonding dry surfaces. Special adhesives, usually based on epoxy resin, have been developed for bonding wet surfaces and for joining structures submerged in water.

To achieve high-quality adhesion of composite material to wood, temperature and humidity conditions at the work site and the quality of surface preparation of the reinforced or strengthened structure are equally important. A contaminated or uneven surface cannot provide the necessary quality of adhesion with the composite material.

Composite materials have found wide application for increasing, restoring load-bearing capacity, and strengthening building structures of various engineering facilities - industrial and residential buildings, bridges, pipes, bunkers, piers, tunnels of various purposes, and are also used for the restoration of architectural monuments.

Considering all these factors, it can be said that reinforcement and strengthening of building structures with composite materials is a less labor-intensive and energy-consuming process compared to other similar strengthening methods. This circumstance is especially important when repairing and strengthening many structures, such as bridges on road and railway highways, where their failure (temporary cessation of operation) during repair works leads to significant financial losses. This explains the growing volume of composite materials application in structural strengthening worldwide. For example, in Switzerland, they are used in more than 80% of cases of strengthening all building structures.

Technology of Reinforcing Glulam Beams with Composite Strips

Input Materials:

- Glulam beam (Fig. 5) manufactured according to the relevant technology;
- Composite strips Sika CarboDur S-512 (Fig. 6a) for strengthening the tension zone of the element;
- Composite fabrics Sika Wrap - 230 C/45 (Fig. 6b) for anchoring the Sika CarboDur S-512 composite strips and for resisting shear forces in the support zone;
- Sika Colma-Cleaner solution for wetting, cleaning, and activating composite strips and fabrics;
- Sikadur-30 and Sikadur-330 adhesives for bonding strips and fabrics, respectively, to the tested specimen.

Fig. 5. Straight glued laminated timber beam with rectangular cross-section 10 × 24 (*h*) cm, length 4 m

(a) (b)

Fig. 6. Composite materials by Sika:
(a) – composite strips Sika CarboDur S-512;
(b) – composite fabrics Sika Wrap - 230 C/45

Before starting the reinforcement of the glued laminated timber beam, hands and exposed skin should be treated with protective cream. Protective clothing must be worn: workwear, safety goggles, respirators, helmets, and gloves. The bonding surface must be clean, degreased, smooth, dry, and free from sawdust and any other contaminants such as dust, foreign particles, oil, grease, surface coatings, or other substances that could negatively affect the adhesion of the system to the beam. The preparation work was carried out mechanically using sandpaper in accordance with technological requirements. On the edges of the beam, where it is wrapped with the Sika Wrap – 230 C/45 fabric, a chamfer with a radius of 2 cm was made.

To bond the Sika CarboDur S-512 composite strips to the beam, they need to be laid out on a clean cloth and activated by thoroughly cleaning with a cloth moistened with Sika Colma-Cleaner solution. After activation, a technological pause of 15 to 30 minutes should be observed. The strips must be cleaned until no black residue appears on the cloth.

During the technological pause, keeping a distance from the strips to avoid moisture, dirt, or other contaminants getting on them, prepare the Sikadur-30 adhesive. Thoroughly mix components A and B in the packaging container. Then add the entire amount of component B to component A and mix (for at least 3 minutes) until a uniform color is obtained. The mixed components A and B should be transferred to a clean container and mixed again for 1 minute. Use a low-speed mixer (up to 600 rpm) for mixing.

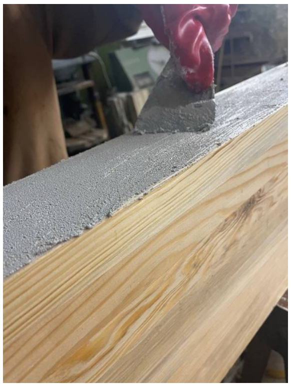
If not all the adhesive is used, follow the mixing ratio specified on the packaging (components A:B = 3:1 by weight), carefully weighing and dosing each part. Next, apply a thin layer of Sikadur-30 adhesive to the strip with a spatula or using a special (pre-made) device (Fig. 7, a) so that in cross-section it forms the shape of a pitched roof with a height of 3 to 5 mm or a semicircle.

The well-mixed Sikadur-30 adhesive should be carefully rubbed into the previously prepared and cleaned surface of the beam with a spatula, leveling any irregularities (Fig. 7, b). The adhesive layer should be at least 1 mm thick.

Attach the Sika CarboDur S-512 strips to the prepared and adhesive-coated element to be reinforced. Press the strips firmly onto the cleaned surface with a roller so that all excess adhesive is squeezed out along both edges of the strip. Remove the excess adhesive with a cloth (Fig. 8).

After 24 hours, the strips will be anchored using unidirectional carbon fiber fabric Sika Wrap - 230 C/45. The material is supplied in rolls. Bending the fabric is strictly prohibited! All bends in the fabric must not exceed the radius of the spool packaging. The fabric should be cut with scissors or a sharp knife. Place the cut piece of fabric on a clean cloth and activate it by thoroughly wiping with a clean cloth moistened with Sika Colma-Cleaner solution. Take a technical break of 15–30 minutes. During activation, avoid dust contamination and ensure a supply of fresh air. Smoking and the use of open flames are strictly forbidden! Work must be carried out wearing protective goggles, rubber gloves, and respirators.

(a)



(b)

Fig. 7. Application of Sikadur-30: (a) – applying Sikadur-30 adhesive on the strip; (b) – applying Sikadur- 30 adhesive on the model surface

During the technical break, keeping a distance from the activated fabrics, prepare the Sikadur-330 adhesive. Thoroughly mix components A and B in containers. Then add the entire amount of component B to component A and mix according to the same procedure as for Sikadur-30. When not using all the adhesive, follow the mixing ratio specified on the packaging (components A:B = 4:1 by weight), carefully weighing and dosing each part. Sikadur-330 must be protected from moisture or condensation for 24 hours.

Fig. 8 Composite strips Sika CarboDur S-512 bonded to the glued laminated timber beam

Apply a layer of Sikadur-330 adhesive to the model base using a spatula, roller, or brush (Fig. 9, a). Saturate the fabric with the Sikadur-330 adhesive. Place the carbon fiber fabric Sika Wrap - 230 C/45 in the required direction (perpendicular to the beam axis) onto the Sikadur-330 layer. Carefully roll the fabric into the adhesive layer with a plastic roller along the fiber direction so that the adhesive penetrates through the fibers and evenly distributes across the entire fabric surface. Avoid folds and creases on the fabric surface (Fig. 9, b). When rolling, avoid excessive force to prevent wrinkling and distortion of the Sika Wrap - 230 C/45 fabric. The overlap length along the fibers must be at least 100 mm.

(a)

(b)

Fig. 9. Application of Sikadur- 330 adhesive: (a) – applying Sikadur- 330 adhesive to the model base; (b) – rolling in Sika Wrap - 230 C/45 fabric into Sikadur- 330 adhesive on the model surface

After the adhesives reach maximum strength (7 days after bonding), sand off any excess adhesive with sandpaper. After this, the beam is fully ready for use.

Modeling of a glued laminated timber beam reinforced with composite strips in the software package LIRA 2024

The geometric scheme of a straight glued laminated timber beam reinforced with composite strips, the main dimensions, support schemes, as well as the schemes and values of external loading forces are shown in Figure 10.

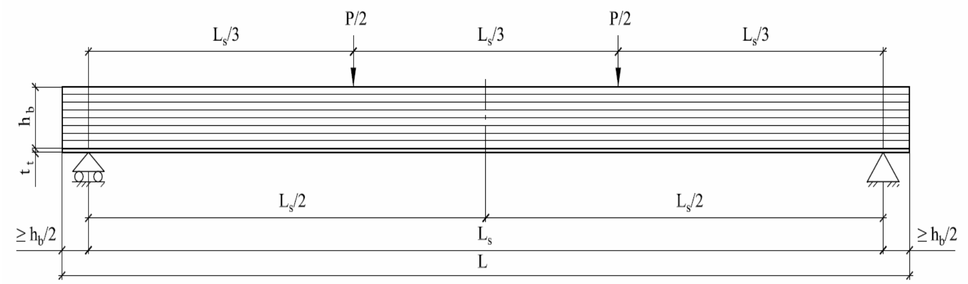


Fig. 10. Calculated geometric scheme of a straight glued laminated timber beam reinforced with composite strips

The beam is fixed to the "ground" using "hinged movable" and "hinged immovable" ties located at the nodes across the entire width of the beam's cross-section, positioned at a distance $\geq h_b/2$.

The beam is loaded with uniformly distributed vertical loads qk along the *Y*-axis, applied at a distance of $L_s/3$ from the supports through a fictitious beam with conditional stiffness. In the LIRA 2024 software environment, the element is modeled using 3D finite elements (FE) № 36. The size of the finite elements for the glued laminated timber beam body is accepted as 1(h)×1×1 cm, with the following mechanical properties:

- modulus of elasticity of wood along the grain: $E_1 = E_{0,\text{mean}} = 12000$ MPa;
- modulus of elasticity of wood perpendicular to the grain: E_2, $E_3 = E_{90,\text{mean}} = 400$ MPa;
- shear modulus: G_{12}, G_{13}, $G_{23} = G_{\text{mean}} = 750$ MPa;
- Poisson's ratios of the wood: $\nu_{12}, \nu_{13}, \nu_{23}, \nu_{32} = \nu_{90} = 0,018$ and $\nu_{21}, \nu_{31} = \nu_0 = 0,48$;
- density of the wood: $R_0 = \rho = 380$ kg/m^3.

The size of the finite elements for the composite strip body is taken as 0.12(h)×1×1 cm, with the following mechanical properties::

- Tensile modulus of elasticity of the strip: $E = 170\,000$ MPa;
- Poisson's ratio: $V = v_0 = 0{,}3$;
- density of the strip: $R_0 = \rho = 1600$ kg/m^3.

The load is applied as linear forces over the entire width of the cross-section of the beam model along the *Z*-axis, at a distance of 125 cm from the supports through a fictitious beam with conditionally low stiffness. The calculation is performed in a linear formulation, taking into account the orthotropic properties of the material. For better validation of the results, separate load cases were created with load values applied along a single axis at 5, 10, 15, and 20 kN.

The restraints are applied in the *X*, *Y*, and *Z* directions in the lower zone across the entire width of the cross-section in the *XOZ* plane on the left side, at a distance of 12.5 cm from the end of the beam, and in the *Z* direction in the lower zone in the *XOZ* plane on the right side, at a distance of 12.5 cm from the beam end.

The composite fabrics Sika Wrap - 230 C/45 were not modeled in the LIRA 2024 software because their thickness is very small and did not affect the results when modeled with solid finite elements.

The final appearance of the numerical model of the element created in LIRA 2024 is shown in Fig. 11.

The obtained stress mosaics for N_x (maximum longitudinal stresses), N_z (maximum transverse stresses), and τ_{xz} (maximum shear stresses) under the maximum load of 20 kN applied along one load axis are shown in Figures 12–14.

The displacement mosaics in the *Z* direction (*G*) (vertical deformations of the model) under the maximum load of 20 kN are presented in Figure 15.

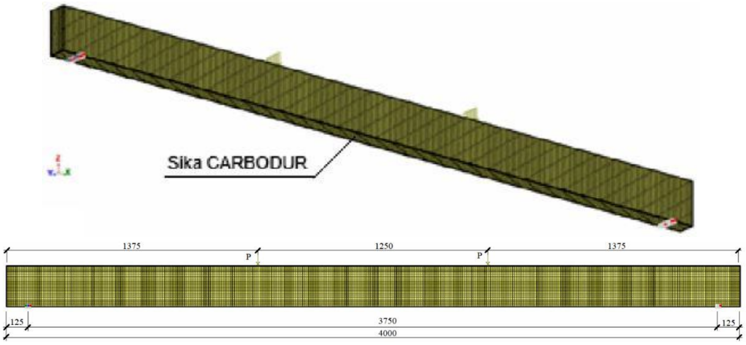


Fig. 11. Numerical model of a rectangular cross-section glued laminated timber element reinforced with composite strips, modeled in LIRA 2024 software

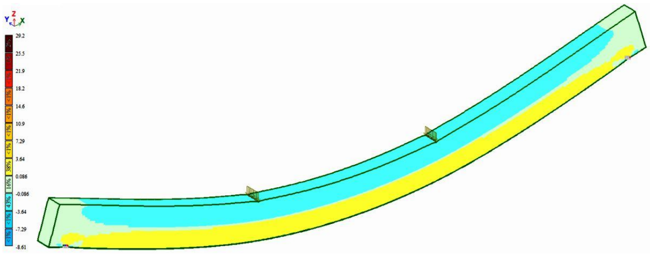


Fig. 12. Stress mosaic for N_x (maximum longitudinal stresses) at maximum loads of 20 kN applied along a single load axis

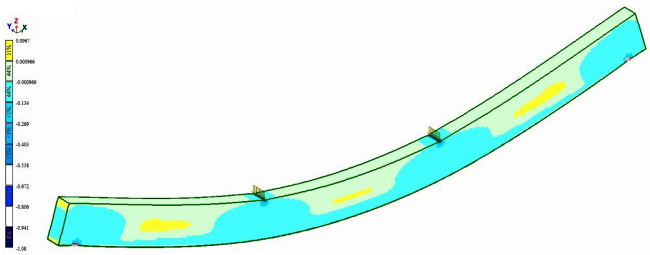


Fig. 13. Stress mosaic for N_z (maximum transverse stresses) at maximum loads of 20 kN applied along a single load axis

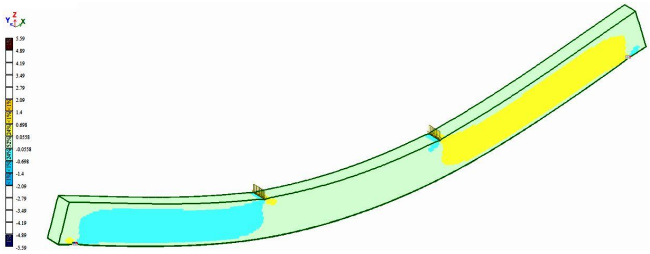


Fig. 14 Stress mosaic for τ_{xz} (maximum shear stresses) at maximum loads of 20 kN applied along a single load axis

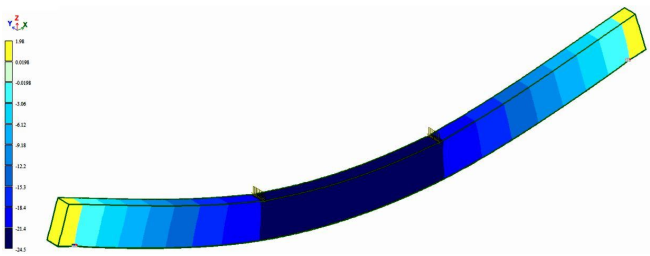


Fig. 15. Displacement mosaic Z (G) (vertical deformations of the model) at maximum loads of 20 kN applied along a single load axis

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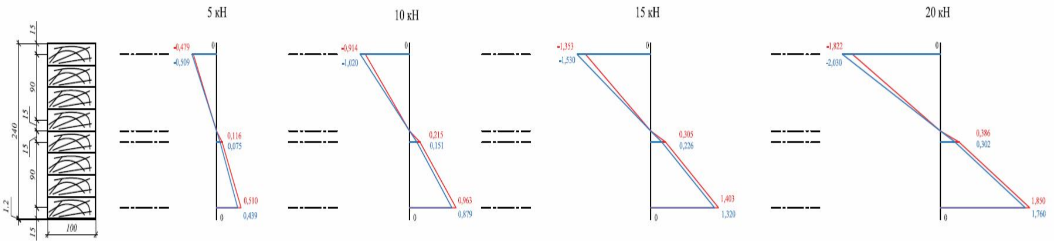
Comparison of Experimental Test Results with Numerical Modeling Results

The determination of the stress-strain state of the glued laminated timber beam reinforced with composite strips by the experimental method is presented in article [19]. It is advisable to compare the results obtained during the experimental study and numerical modeling according to the stress values. Diagrams comparing the maximum longitudinal stresses in the main investigated timber cross-sections (at the mid-span, at the axis of applied linear load, and at the support axis) are shown in Fig. 16, as well as the graph of maximum vertical deformations from the experiment in Fig. 17.

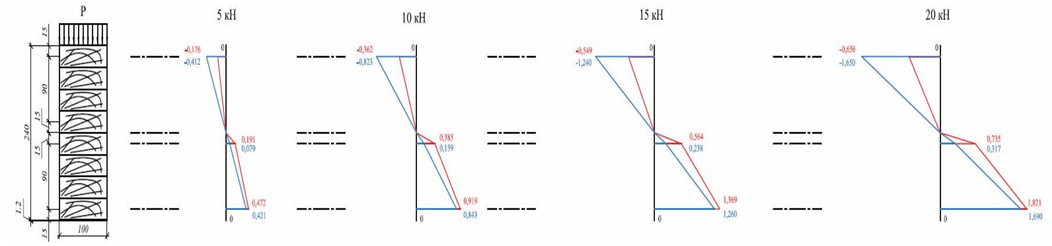
Diagrams of maximum longitudinal stresses in the wood at the mid-span corresponding to the given load values



– the element is reinforced with composite tapes -0,479 the element is reinforced with composite tapes

– the element model is not reinforced in the LIRA -0,509 the element model is not reinforced in the LIRA

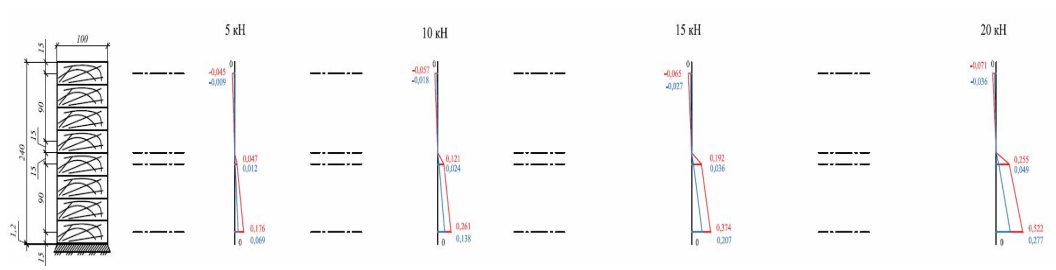
Diagrams of maximum longitudinal stresses in the wood along the axis of load application at the corresponding load values



– the element is reinforced with composite tapes -0,176 the element is reinforced with composite tapes

– the element model is not reinforced in the LIRA -0,412 the element model is not reinforced in the LIRA

Diagrams of maximum longitudinal stresses in the wood at the support section for the corresponding load values



– the element is reinforced with composite tapes -0,045 the element is reinforced with composite tapes

– the element model is not reinforced in the LIRA -0,009 the element model is not reinforced in the LIRA

Fig. 16. Maximum longitudinal stresses in the wood of the investigated sections of the experimental specimen and the experimental specimen model in the LIRA software reinforced with composite strips, at load values of 5, 10, 15, and 20 kN, applied along a single load axis

The difference in maximum longitudinal stresses in the timber of the investigated cross-sections between the experimental specimen and the numerical model of the experimental specimen in the LIRA software, reinforced with composite strips, is up to 12% in the compressed zone, up to 36% in the middle zone, and up to 14% in the tension zone at mid-span. The difference in maximum longitudinal stresses along the load application axis is up to 61% in the compressed zone, up to 59% in the middle zone, and up to 11% in the tension zone.

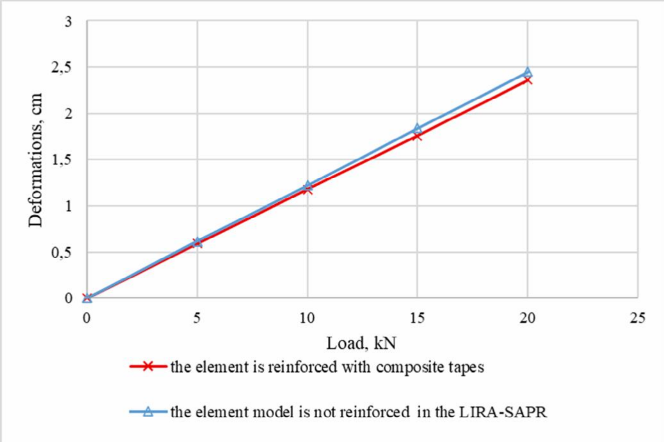


Fig. 17. Graph of maximum vertical deformations of the experimental specimen reinforced with composite strips and the experimental specimen model in LIRA software reinforced with composite strips, at load values of 5, 10, 15, and 20 kN applied along a single load axis

The difference in maximum vertical deformations between the experimental specimen and the numerical model of the experimental specimen in LIRA, reinforced with composite strips, at load values of 5, 10, 15, and 20 kN applied along a single axis is up to 4%, which indicates very good convergence.

The qualitative nature of the stress state of the timber obtained from the numerical study is confirmed by the experiment. Overall, the longitudinal stresses in the tensile zone of the investigated cross-sections show good agreement. Some discrepancies in the quantitative values of transverse and shear stresses can be explained by the peculiarities of the timber structure and the presence of factors that can significantly affect its stress-strain state and, consequently, its overall strength. These factors include fiber inclination, the presence of knots, and infestation by any type of wood-decaying fungi. Electrical strain gauge measurements are very sensitive to the heterogeneous structure of the timber. In the software package, the timber is modeled as an idealized material.

Comparison of Experimental Results of Reinforced and Non-Reinforced Glulam Beams.

By analogy with the determination of the stress-strain state of a glued laminated timber beam reinforced with composite strips using the experimental method described in article [19], the stress-strain state of a glued laminated timber beam without reinforcement was also determined. Therefore, it is appropriate to compare the results obtained during such experimental studies.

It has been experimentally proven that the adopted modulus of elasticity of wood in bending $E_{m,g}$ = 1200 кN/cm^2, corresponds to the actual modulus of elasticity of the investigated non-reinforced experimental specimen and equals the arithmetic mean value $E_{m,g}$ = 1205,42 кN/cm^2.

The analysis of the stress-strain state of the experimental specimen without reinforcement and reinforced with composite strips under load values of 5, 10, 15, and 20 kN applied along one axis clearly shows that the composite strips Sika CarboDur S512, bonded to the tension zone of the glued laminated timber beam, reduce vertical deformations (Fig. 18) by up to 13%.

The determination of stresses was performed using formulas 1-3:

$$\sigma_x = E_x \cdot \left(\frac{\varepsilon_x + \nu_{yx} \cdot \varepsilon_y}{1 - \nu_{xy} \cdot \nu_{yx}} \right), \quad (1)$$

$$\sigma_y = E_y \cdot \left(\frac{\varepsilon_y + \nu_{xy} \cdot \varepsilon_x}{1 - \nu_{xy} \cdot \nu_{yx}} \right), \quad (2)$$

$$\tau_{xy} = G \cdot \left[2\varepsilon_{45} - \left(\varepsilon_x + \varepsilon_y \right) \right], \quad (3)$$

where E_x, E_y - elastic modules of wood along and across the grain, respectively; ν_{xy}, ν_{yx} - coefficients of transverse strain (Poisson's ratios) of wood; G - shear modulus of wood; ε_x, ε_y, ε_{45} - relative strains along, across, and at 45° to the wood fibers.

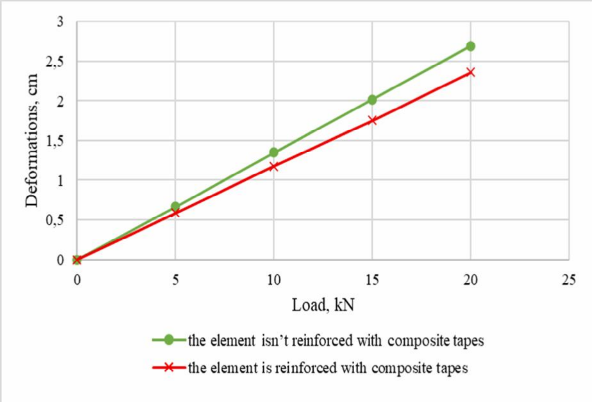


Fig. 18. Graph of maximum vertical deformations of the experimental specimen without reinforcement and reinforced with composite strips, at load values of 5, 10, 15, and 20 kN applied along a single load axis

Relative strains are determined by the formula $\varepsilon_i = (\Delta_i - \Delta_0) \cdot n$, in which $n = 2 \cdot 10^{-6}$ - he scale division value of the "CIIT-3" strain gauge is.

Based on the obtained stress values, diagrams comparing the maximum longitudinal stresses in the main studied cross-sections of the timber (at the mid-span, at the axis of applied linear load, and at the support axis) of the experimental specimen without reinforcement and reinforced with composite strips under load values of 5, 10, 15, and 20 kN applied along one load axis are presented in Fig. 19.

For a more detailed analysis of stresses in the studied cross-sections, we divide them into three investigation zones, namely:

1. Compressed zone (in the first board from the top of the glued cross-section);
2. Middle zone (in the fifth board from the top of the glued cross-section);
3. Tension zone (in the eighth board from the top of the glued cross-section).

The maximum longitudinal stresses σ_x in the mid-span decreased by up to 7% in the compressed zone, up to 33% in the middle zone, and up to 10% in the tension zone. The maximum longitudinal stresses along the axis of the applied load decreased by up to 42% in the compressed zone, up to 16% in the middle zone, and up to 38% in the tension zone. The maximum longitudinal stresses near the support decreased by up to 35% in the middle zone and up to 25% in the tension zone.

Thus, we can conclude that reinforcement with composite strips redistributes stresses in the wood, reducing longitudinal stresses in all investigated cross-sections. The difference in the reduction of longitudinal stresses in the investigated cross-sections in the tension zone increases with increasing loads.

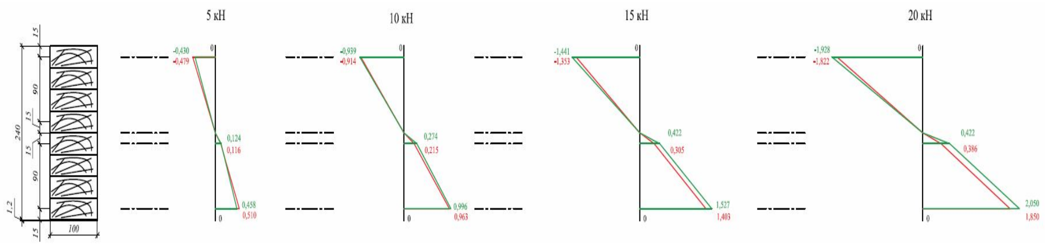
The failure of the experimental specimen reinforced with composite strips occurred at a load of 30 kN applied along one loading axis. The failure took place in the cross-section at the axis of load application near one of the indicated initial defects in the zone of maximum stress concentration. The general appearance and the schematic of the experimental specimen after the first signs of strength loss are shown in Fig. 20.

Calculation of glued laminated timber beams reinforced with composite strips

The geometric scheme of a straight glued laminated timber beam reinforced with composite strips, the main dimensions, support schemes, as well as the schemes and values of the external load forces are shown in Fig. 10.

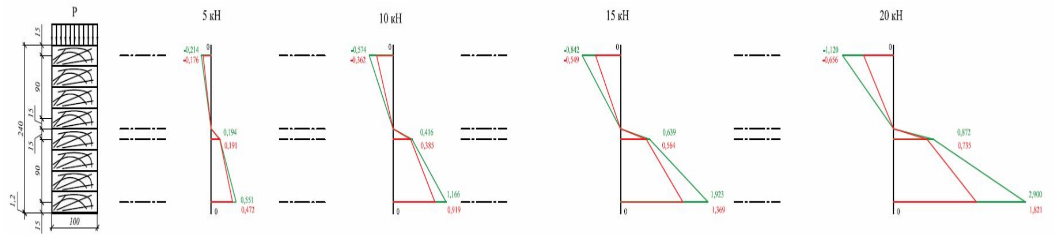
When determining the principal stresses in glued laminated timber beams reinforced with composite strips, any of the known methods can be used. For detailed stress analysis across the entire cross-section of the beams and to simplify calculations, in this article, the determination of stresses in glued laminated timber beams reinforced with composite strips is performed by modeling and calculation using the finite element method in the LIRA 2024 software package.

Diagrams of maximum longitudinal stresses in the wood at the mid-span corresponding to the given load values



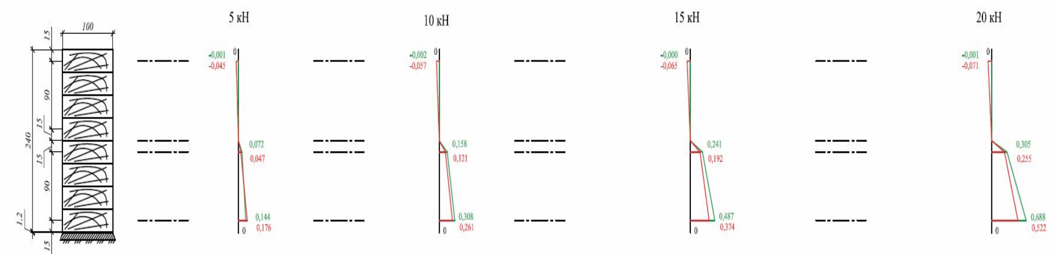
– the element isn't reinforced with composite tapes -0,430 the element isn't reinforced with composite tapes
– the element is reinforced with composite tapes -0,479 the element is reinforced with composite tapes

Diagrams of maximum longitudinal stresses in the wood along the load application axis at the corresponding load values



– the element isn't reinforced with composite tapes -0,214 the element isn't reinforced with composite tapes
– the element is reinforced with composite tapes -0,176 the element is reinforced with composite tapes

Diagrams of maximum longitudinal stresses in the wood at the support axis for the corresponding load values



– the element isn't reinforced with composite tapes -0,001 the element isn't reinforced with composite tapes
– the element is reinforced with composite tapes -0,045 the element is reinforced with composite tapes

Fig. 19. Maximum longitudinal stresses in the wood of the studied sections of the experimental specimen without reinforcement and reinforced with composite strips, at load values of 5, 10, 15, 20 kN applied along a single load axis.

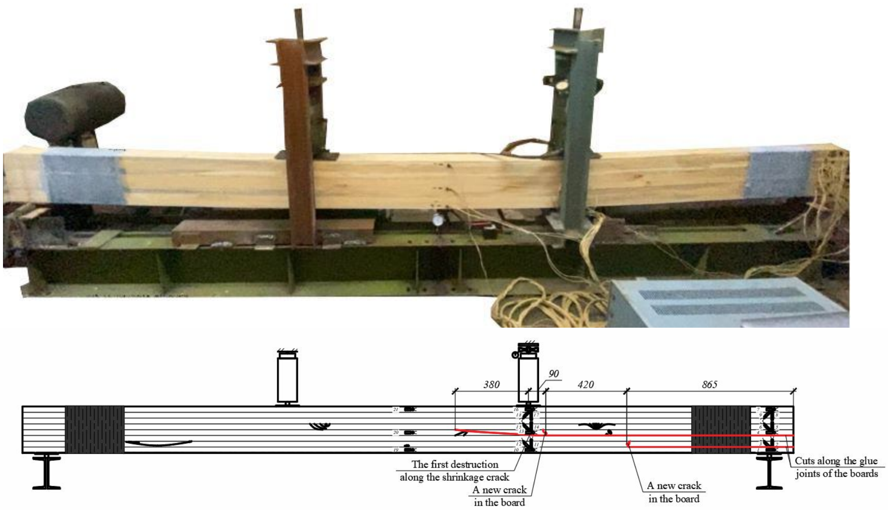


Fig. 20. General view and scheme of the experimental specimen after the first signs of strength loss

Calculations of beams according to the first group of limit states (limit states of bearing capacity)

The strength of a glued laminated timber beam under normal bending stresses is checked using the general formula:

$$\frac{\sigma_{m,d}}{f_{m,d}} \leq 1, \quad (4)$$

where $\sigma_{m,d}$ – normal bending stresses in the timber beam are determined by calculation in the LIRA 2024 software; $f_{m,d}$ - calculated bending strength of wood.

The strength of the beam in the support zone is checked for maximum splitting stresses using the formula:

$$\frac{\tau_d}{f_{v,d}} \leq 1, \quad (5)$$

where τ_d - design shear stress, which is determined from the calculation in the LIRA 2024 software; $f_{v,d}$ - design value of shear strength.

Stability check of the beam's planar deformation form is performed using the formula:

$$\frac{\sigma_{m,d}}{k_{\text{crit}} \cdot f_{m,d}} \leq 1, \quad (6)$$

where $\sigma_{m,d}$ – normal stresses due to bending; $f_{m,d}$ - calculated bending strength of wood. k_{crit} - coefficient calculated using the formula:

$$k_{\text{crit}} = \begin{cases} 1 & \text{when} \quad \lambda_{\text{rel},m} \leq 0.75 \\ 1.56 - 0.75\lambda_{\text{rel},m} & \text{when} \quad 0.75 < \lambda_{\text{rel},m} \leq 1.4 \\ 1/\lambda_{\text{rel},m}^2 & \text{when} \quad 1.4 < \lambda_{\text{rel},m} \end{cases}, \quad (7)$$

where $\lambda_{\text{rel},m}$ – relative flexibility of the element.

Calculation of Composite Reinforcement of a Glued Laminated Timber Beam for the Ultimate Limit State (Load-Bearing Capacity Limit State)

The strength of the composite reinforcement under tensile normal stresses is verified by the general formula:

$$\frac{\sigma_t}{f_t} \leq 1, \quad (8)$$

where σ_t – normal tensile stresses in the composite reinforcement are determined in the LIRA 2024 software.; f_t - the design value of the tensile strength of the composite reinforcement is specified in the material data sheet.

Calculations according to the second group of limit states (serviceability limit states)

The total net deflection can be determined using commonly accepted formulas taking into account the transformed section properties to wood, or according to the calculations performed in the LIRA 2024 software.

The equivalent modulus of elasticity of the cross-section of glued laminated timber beams reinforced with composite strips is determined from the condition:

$$I_{x,ef} \cdot E_{x,b} = I_{x,b} \cdot E_{x,ef}, \quad (9)$$

where $I_{x,ef}$ – the transformed moment of inertia of the cross-section perpendicular to the *X*-axis, which should be determined by formula 10; $E_{x,b}$ – modulus of elasticity of wood along the grain; $I_{x,b}$ – moment of inertia of the glued laminated timber beam cross-section relative to the neutral axis; $E_{x,ef}$ – equivalent modulus of elasticity of the glued laminated timber element reinforced with a composite strip along the tensile fibers.

From formula (9), we obtain the formula for determining the equivalent modulus of elasticity of the glued laminated timber element reinforced with a composite strip along the tensile fibers:

$$E_{x,ef}=\frac{I_{x,ef}\cdot E_{x,b}}{I_{x,b}}. \quad (10)$$

Moment of inertia of the section transformed to the timber:

$$I_{x,ef}=I_{x,b}+I_{x,a}\cdot\frac{E_{x,a}}{E_{x,b}}, \quad (11)$$

where $I_{x,b}$ – moment of inertia of the cross-section of the glued laminated timber beam relative to the neutral axis; $I_{x,a}$ – moment of inertia of the reinforcement cross-section relative to the neutral axis; $E_{x,b}$ – modulus of elasticity of the boards relative to the x-axis, along the grain; $E_{x,a}$ – modulus of elasticity of the reinforcement along the fibers.

Equivalent cross-sectional area referred to the wood:

$$A_{x,ef}=A_{x,a}\cdot\frac{E_{x,a}}{E_{x,b}}, \quad (12)$$

where $A_{x,a}$ – cross-sectional area of the reinforcement; $E_{x,b}$ – modulus of elasticity of the boards relative to the x-axis, along the grain; $E_{x,a}$ – modulus of elasticity of the reinforcement along the fibers.

The transformed section modulus relative to the wood:

$$W_{x,ef}=\frac{I_{x,ef}}{h_z}, \quad (13)$$

where $I_{x,ef}$ – the transformed moment of inertia of the cross-section perpendicular to the x-axis, which should be determined by formula11; h_z – distance from the centroid of the cross-section to the extreme fiber where the stress is determined.

Strength calculations under complex stress state

After ensuring the strength in the calculation of wooden structural elements according to the ultimate limit states, the identification of zones of maximum stress concentration can be carried out by any convenient known method. However, the most effective method is modeling the elements in software complexes using three-dimensional finite elements for detailed stress analysis throughout the entire volume of the element.

The zones of maximum stress concentration are located where the highest maximum transverse stresses in the wood occur, along with the corresponding maximum longitudinal and shear stresses.

We determine the strength conditions under a complex stress state (CSS) at the point of maximum stress concentration, which is performed using formula 14 under the action of нормальних normal compressive stresses (σ_c), shear stresses (τ) and tensile stresses perpendicular to the grain ($\sigma_{t.90}$):

$$\frac{\sigma_c^2}{\left(f_{c,0,d}\right)^2}+\frac{\sigma_{t,90}^2}{\left(f_{t,90,d}\right)^2}A_{c,t}-\frac{\sigma_c\sigma_{t,90}}{f_{c,0,d}f_{t,90,d}}C_{c,t}+\frac{\tau^2}{\left(f_{v,d}\right)^2}B_{c,t}\le 1, \quad (14)$$

where σ_c - normal compressive stresses along the wood grain; τ - shear (splitting) stresses; $\sigma_{t,90}$ - normal tensile stresses perpendicular to the wood grain; $f_{c,0,d}$ – design value of wood compressive strength along the grain; $f_{t,90,d}$ – design value of wood tensile strength perpendicular to the grain; $A_{c,t}$, $C_{c,t}$, $B_{c,t}$ – parameters accounting for the anisotropy of physical and mechanical properties and the initial level of normal stresses along the fibers [20].

Definition of zones of maximum stress concentration

Definition of zones of maximum stress concentration using the LIRA software by the finite element method was carried out by investigating the maximum stresses in the finite elements of the beam cross-section.

After the analysis, it was determined that the zones of maximum stress concentration are located where the greatest maximum transverse stresses in the wood occur, along with the corresponding maximum longitudinal and shear stresses. The zones of maximum stress concentration are shown in Fig. 21.

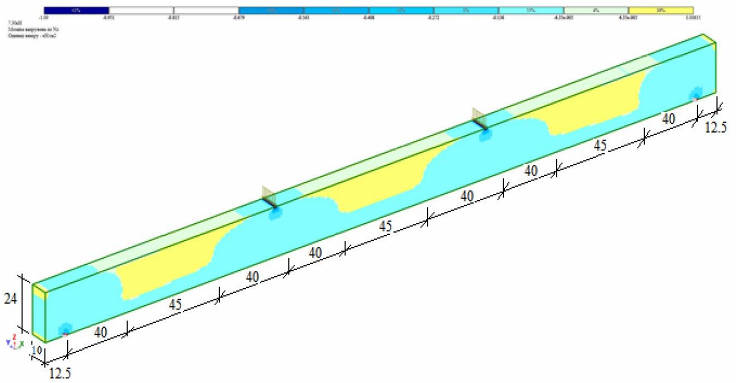


Fig. 21. Beam with a 4 m span and zones of concentration of maximum shear stresses

To reduce stress concentration in these zones, it is proposed to reinforce them using Sika Wrap – 230 C/45 composite sheets with two variants.

Variant №1. External wrapping of the beam body in the zones of maximum stress concentration with Sika Wrap – 230 C/45 sheets. The algorithm for wrapping the beam body with the sheets is provided in the section "Technology of reinforcing glued laminated timber beams with composite strips." The reinforcement scheme of the zones of maximum stress concentration in glued laminated timber beams reinforced with composite strips according to variant No. 1 is shown in Fig. 22.

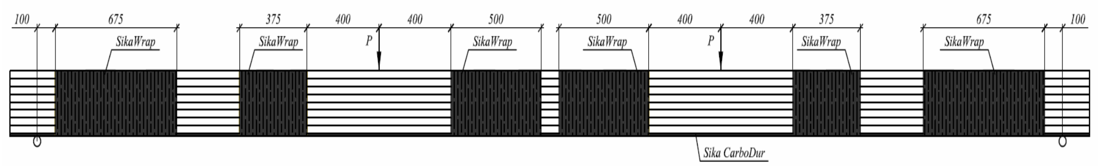


Fig. 22. Reinforcement scheme of zones of maximum stress concentration in glued laminated timber beams strengthened with composite strips according to Variant №1

Variant №2. In the zones of maximum stress concentration, cylindrical grooves are made along the central axis of the beam's cross-section width at a 45° angle. Into the manufactured grooves, glue-soaked and twisted into tubes sheets of Sika Wrap – 230 C/45 are inserted, forming a so-called composite rod. In this scheme, the Sika Wrap – 230 C/45 sheets are wrapped around the beam body in the support zones for better anchoring of the Sika CarboDur S512 strips. The reinforcement scheme of the maximum stress concentration zones in glued laminated timber beams reinforced with composite strips according to variant No. 2 is shown in Fig. 23.

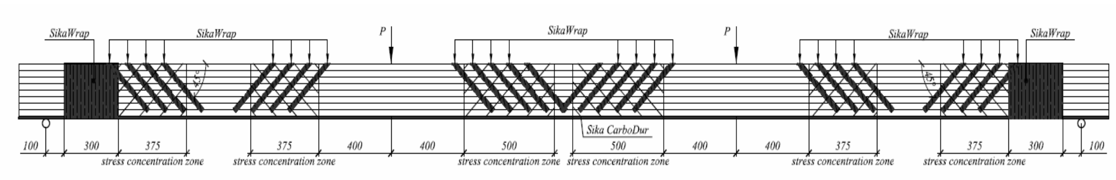


Fig. 23. Reinforcement scheme of zones of maximum stress concentration in glued laminated timber beams strengthened with composite strips according to Variant №2

Conclusions

The obtained results can be used in studies of reinforcement and strengthening of other types of building structures.

The presented technology for reinforcing wooden beams can be applied in research on other reinforced wooden structures.

From the graph of vertical deformations depending on applied loads on a beam reinforced with composite strips (Fig. 17), a linear behavior of the structure under significant loads applied along one load axis can be observed.

It has been experimentally proven that reinforcing glued laminated timber beams with composite strips causes a redistribution of internal stresses in the design sections of the beam. Longitudinal stresses in the timber of the tensile zone significantly decrease, while normal stresses perpendicular to the grain and shear stresses increase. Therefore, when strengthening wooden structures with composite strips, it is necessary not only to perform mandatory strength checks for normal tensile stresses according to [11], but also to pay special attention to strength checks for maximum stresses perpendicular to the grain and shear stresses, as well as their combined effect (complex stress state).

3D finite element modeling allows detailed study of stresses and displacements in any section of the element; however, such modeling is quite labor-intensive and resource-consuming. Modeling entire systems composed of such elements can overload the software. Therefore, to simplify system calculations, it is recommended to model elements as rod or shell finite elements with equivalent cross-sectional properties for timber, according to formulas 9 – 13.

Reinforcement of glued laminated timber beams by bonding composite strips to the tensile zone reduces vertical deformations by up to 13%, which correlates well with the numerical modeling results in the LIRA software, where vertical deformations in specimens reinforced with composite strips decreased by up to 17%.

The qualitative nature of the timber stress state obtained from numerical analysis is confirmed experimentally; overall, longitudinal stresses in the tensile zone of the investigated sections show good agreement. Some differences in quantitative values of transverse and shear stresses are explained by the specific structure of timber and factors that significantly influence its stress-strain state and, consequently, its overall strength. These factors include fiber inclination, presence of knots, and fungal infection of any kind. Electrotensometry is very sensitive to timber heterogeneity. In the software package, timber is modeled as an idealized orthotropic material.

Failure of the glued laminated timber beam reinforced with composite strips occurred in a zone of combined maximum transverse, longitudinal, and shear stresses, which confirms the calculation and the necessity of strength verification under a complex stress state.

It is important to note that the latest versions of European Union standards (such as Eurocode 5 or EN 1995-1-1:2008 [13]) and Ukrainian codes (DBN V.2.6-161:2017 [14], DSTU-N B V.2.6-184:2012 [21],) lack methodological recommendations for the design and calculation of glued laminated timber structures reinforced with composite strips.

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БАЛКА З КЛЕЄНОЇ ДЕРЕВИНИ АРМОВАНА КОМПОЗИТНИМИ СТРІЧКАМИ

Актуальність. Сучасні тенденції у розвитку будівельної галузі вимагають все більшої уваги до екологічних аспектів. Це зумовлює зростання популярності матеріалів, які є екологічно безпечними та мають мінімальний негативний вплив на довкілля. Водночас такі матеріали повинні володіти високою міцністю та стійкістю до зовнішніх впливів і навантажень. З огляду на це, широкого застосування набувають конструкції з деревини. Вони виготовляються з відновлюваних природних ресурсів, вирізняються відносно високою міцністю при невеликій вазі, що дозволяє віднести їх до екологічних будівельних матеріалів. Незважаючи на деякі недоліки деревини, зокрема схильність до усушки, гниття та анізотропні фізико-механічні властивості, у конструкціях з клеєної деревини ці недоліки можуть бути майже повністю усунені. Зокрема, балки з клеєної деревини є ключовим елементом багатьох конструкцій та надзвичайно поширені у будівництві. Тому питання підвищення їх жорсткості та міцності шляхом армування композитними матеріалами набуває особливої актуальності.

Мета роботи. Метою даної роботи є представлення алгоритмів армування балок з клеєної деревини композитними стрічками, порівняння результатів експериментальних досліджень з чисельним дослідженням напружено-деформованого стану та представлення методики розрахунку балки з клеєної деревини підсиленої композитними стрічками за двома групами граничних станів.

Результати. У статті запропоновано технологію армування, методику визначення напружено-деформованого стану, методику розрахунків балки з клеєної деревини армованої композитними стрічками. Наведено результати параметрів деформування експериментальної моделі, фактичні модулі пружності при згині, максимальні повздовжні напруження по центру прольоту, по осі прикладання навантаження та по осі опори. Визначено фактичну максимальну несучу здатність експериментальної моделі армованої композитними стрічками. Та наведено порівняння з чисельними дослідженнями в сучасному програмному комплексі.

Ключові слова: армування клеєної деревини, деформації, електротензометрія, клеєна деревина, конструкції з клеєної деревини, композитні стрічки, напружено-деформований стан, напруження.

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GLUED LAMINATED TIMBER BEAM REINFORCED WITH COMPOSITE STRIPS

Abstract. Modern trends in the development of the construction industry demand increased attention to environmental aspects. This leads to the growing popularity of materials that are environmentally friendly and have minimal negative impact on the environment. At the same time, such materials must possess high strength and resistance to external influences and loads. In this context, timber structures are gaining widespread use. They are made from renewable natural resources and are characterized by relatively high strength and low weight, which qualifies them as sustainable building materials. Despite certain disadvantages of wood, such as shrinkage, decay, and anisotropic physical and mechanical properties, these drawbacks can be almost completely eliminated in glued laminated timber structures. In particular, glued laminated timber beams are key elements in many structures and are widely used in construction. Therefore, the issue of increasing their stiffness and strength through reinforcement with composite materials is especially relevant.

This paper proposes a reinforcement technology, a methodology for determining the stress–strain state, and a calculation method for glued laminated timber beams reinforced with composite strips. The results of deformation parameters of the experimental model are presented, including actual flexural modules of elasticity, maximum longitudinal stresses at mid-span, at the load application axis, and at the support axis. The actual maximum load-bearing capacity of the experimental model reinforced with composite strips is determined and compared with numerical studies conducted in a modern software package.

Keywords: composite strips, deformations, electrostrain measurement, glued laminated timber, glued timber structures, reinforcement of glued laminated timber, stress–strain state, stresses.

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Запропоновано технологію армування, методику визначення напружено-деформованого стану, методику розрахунків балки з клеєної деревини армованої композитними стрічками. Наведено результати параметрів деформування експериментальної моделі, фактичні модулі пружності при згині, максимальні повздовжні напруження по центру прольоту, по осі прикладання навантаження та по осі опори. Визначено фактичну максимальну несучу здатність експериментальної моделі армованої композитними стрічками. Та наведено порівняння з чисельними дослідженнями в сучасному програмному комплексі.

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The technology of reinforcement, the methodology for determining the stress-strain state, and the calculation method for glued laminated timber beams reinforced with composite strips have been proposed. Results of deformation parameters of the experimental model, actual bending modules of elasticity, maximum longitudinal stresses at the mid-span, at the load application axis, and at the support axis are presented. The actual maximum load-bearing capacity of the experimental model reinforced with composite strips has been determined. A comparison with numerical studies performed in a modern software package is also provided.

Fig. 23. Ref. 35.

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