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DEFINITION OF THE STRESS-STRAIN STATE OF A GLUED LAMINATED TIMBER BEAM REINFORCED WITH COMPOSITE STRIPS USING EXPERIMENTAL METHOD

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The trend in the development of the construction industry worldwide requires increasing attention to ecological aspects, which means that materials with minimal negative impact on the environment are becoming increasingly popular. At the same time, these materials must possess high strength and durability against various external influences and loads. From this perspective, constructions made of wood and its derivatives are gaining the most popularity. Such constructions, made from renewable natural resources, exhibit relatively high strength at relatively low density, thus belonging to such materials. Although wood has its drawbacks, such as susceptibility to drying, rotting, and anisotropy of properties, these drawbacks can be completely mitigated in glued laminated timber structures. Glued laminated timber beams, which are the primary structural element of many buildings and structures, are the most widespread. Therefore, the issue of significantly increasing their rigidity and strength through reinforcement with composite materials is particularly relevant.

This article proposes a methodology for determining the stress-strain state of a glued laminated timber beam reinforced with composite strips. The results include deformation parameters of the experimental model, actual elastic modules during bending, maximum longitudinal stresses at the center of the span, along the load application axis, and along the support axis. Additionally, maximum transverse and shear stresses along the load application axis and along the support axis are determined. The actual maximum load-bearing capacity of the experimental model reinforced with composite strips is established.

Keywords: electrotensometry, clock-type indicator, glued laminated timber, glued laminated timber constructions, composite strips, stress, stress-strain state, reinforcement with composite strips, strain gauges.

Introduction

In modern construction, there is an increasing demand for materials that are environmentally friendly and have minimal negative impact on the environment. At the same time, these materials must possess high strength and durability against various external influences. Timber constructions, made from renewable natural resources and characterized by relatively high strength, belong to such materials [1, 2]. Although wood has its drawbacks, such as susceptibility to drying, rotting, and anisotropy of properties, these issues are more controlled in glued glued laminated timber (GLT) constructions. Beams, which are key elements of GLT, can significantly increase their stiffness and strength through reinforcement with composite materials.

To determine the stress-strain state (SSS) of GLT beams reinforced with composite strips under experimental conditions, the method of electrotensometry and individual measurements of vertical deformations using a clock-type indicator (CTI) were utilized.

It has been confirmed that the proposed results for determining the SSS of GLT beams reinforced with composite strips are suitable for application in calculations, both for individual elements and complex systems derived from them. Specifically, reinforcing GLT beams with composite strips proves to be an effective method for increasing the load-bearing capacity of such constructions.

Literature review

In Ukraine, there is extremely limited experience in designing glued laminated timber (GLT) constructions with rectangular cross-sections reinforced with composite strips. Most studies on such reinforcement are dedicated to reinforced concrete structures [3-5]. In the work by S. Homon and M. Polishchuk, [6] the technology of manufacturing glued laminated timber beams reinforced with rod reinforcement and composite strips is experimentally investigated. The article by O. Bashinsky, T. Bondarchuk, and M. Peleshko [7] describes some results of experimental studies, including three

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methods of reinforcing timber beams with strip reinforcement, practically doubling their load-bearing capacity. Results of numerical studies on the application of composite strips to reinforce various solid and glued laminated timber structures are provided in other works [8, 9].

It is important to note that in the latest versions of the regulatory documents of the European Union (such as Eurocode 5 or EN 1995-1-1:2008 [10]) and Ukraine (DBN V.2.6-161:2017 [11]), there are no methodological recommendations regarding the design and calculation of glued laminated timber structures reinforced with composite strips.

These research findings confirm the need and effectiveness of conducting similar studies on the reinforcement of glued laminated timber structures.

The purpose and tasks of research

The aim of this work is to present the results of an experimental study of the stress-strain state of a glued laminated timber beam reinforced with composite strips.

The object of the research is a glued laminated timber beam with a cross-section dimension of $h_b \times b_b = 24 \times 10$ cm, consisting of 8 layers of boards with a thickness of $t = 3$ cm, with a length of $L = 400$ cm and a working span of $L_p = 375$ cm. The timber used for the beam was pine wood of the 3rd grade, grown in the Rivne region of Ukraine. In the tension zone of the beam, composite strips made of carbon fibers *Sika CarboDur S* 512 with a cross-section dimension of h_a x $b_a = 0.125$ cm were adhered across the entire width of the cross-section according to technological requirements [12-15]. At a distance of 10 cm from the support axes, composite sheets *Sika Wrap* - 230 C/45 with a width of 30 cm were adhered to anchor the composite strips *Sika CarboDur S* 512. The tested beam is supported on two hinged supports and loaded with two concentrated forces at distances of ¼ and ¾ of the span.

The investigation of the stress-strain state of the glued laminated timber beam reinforced with composite strips was conducted using the method of electrotensometry and separate measurements of vertical deformations using a clock-type indicator (CTI).

Preparation for conducting experimental research

To conduct the experiment and determine stress values, the modulus of elasticity of the wood was preliminarily determined according to [16].

Fiber deformations in the cross-sections were measured using electrotensometry. Strain gauges were connected to a static deformation meter "CIIT-3" (manufactured by the Krasnodar Plant of Strain Gauge Instruments, block numbers: BI No.307, DRP No.309) through a remote relay switching unit (RRSU). Type KF5P1-10-200-B-12 strain gauges with a base of 10 mm, manufactured at the Experimental Plant of Portion Automats named after F.E. Dzerzhinsky, were used in the experiment. For measuring fiber deformations in the middle of the span, individual strain gauges were installed longitudinally, one on each outer board of the beam cross-section and one on the fourth board from the bottom (one of the two central boards) in the cross-section. For measuring fiber deformations in the support zone and in the zone of concentrated loads (only on the right side of the beam's symmetry axis, as they should be similar on the left side), strain gauge rosettes - with 3 strain gauges for one point, were installed. They were positioned along the sample axis, perpendicular to the axis, and at a 45° angle to the longitudinal symmetry axis.

After connecting the strain gauges, jacks connected to an oil station were placed at distances of ¼ and ¾ of the span of the model, arranged sequentially to ensure equal pressure in them according to the law of connected vessels. A dynamometer DOS-5 was installed on the piston of the jack located on the right side of the model's symmetry axis, through a steel layer with a diameter of 20 mm, which was installed in a special recess on the piston. The dynamometer was pressed from above by a mechanical screw jack of the loading frame in such a way that it prevented movement of the dynamometer on one side and the indicator reading on the dynamometer was set to "0" using a clock-type indicator according to the pre-conducted calibration.

Steel plates with a length not exceeding half the height of the cross-section of the test specimen were inserted between the sample and the jacks and supports to minimize local wood embedment.

A clock-type indicator was installed under the symmetry axis of the model (in the middle of the span) in such a way that the measuring rod of the indicator could move freely and reached the symmetry axis of the experimental specimen to determine the magnitude of vertical deformations from the applied load.

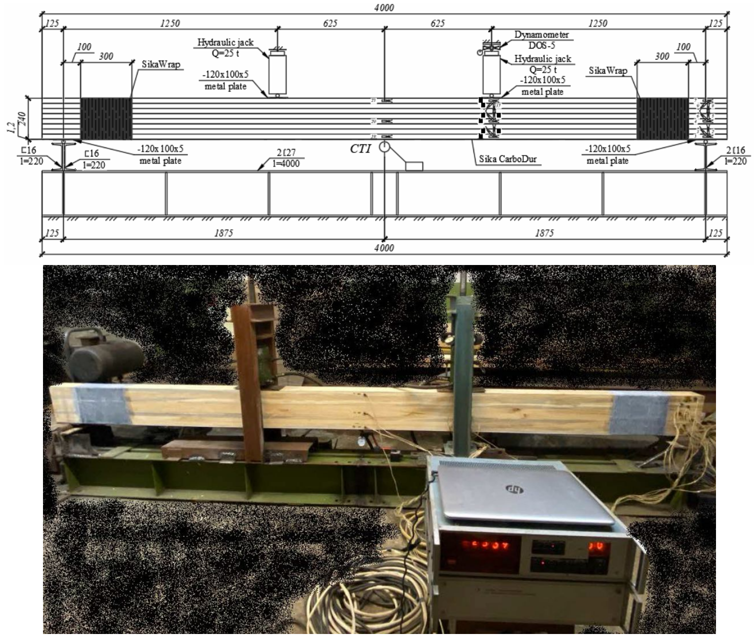


Fig. 1. Arrangement scheme of measuring instruments and a photograph of the experimental setup

Conducting experimental research

For experimental research, each test was divided into a certain number of consecutive loads, and each load was divided into several stages:

- Loading the model;
- Allowing the structure to withstand the load for 15 minutes;
- Recording the readings of the clock-type indicator (CTI);
- Recording the readings of the strain gauge station "CIIT-3";
- Proceeding to the next load step with repetition of the above stages.

Using the pump of the oil station, the necessary reading was set on the dynamometer indicator corresponding to the required load for the current loading step.

The readings of the strain gauges were taken 5 times for each channel of the strain gauge system for each load as follows:

- After the previous load, the strain gauge channel was reset by pressing the button "Sbros";
- обирався необхідний канал кнопкою button "ODNOKR";
- The "NACHALO" and "KONEC" buttons were pressed sequentially;
- The reading was then taken by pressing the button "PUSK";
- Each reading was recorded in the table, taking into account the sign..

Step loading of the models was carried out with a step of 5 kN on one load axis, and loading was continued until the first damage to the experimental model occurred. After that, the model was unloaded and stabilized, and then the readings were taken in the "zero" position.

As a result of the experiment, the deformation parameters of the experimental models, actual elastic modules during bending, maximum longitudinal stresses at the center of the span, along the load application axis, and along the support axis, as well as maximum transverse and tangential stresses along the load application axis and along the support axis, were determined. The actual maximum load-bearing capacity of the experimental model reinforced with composite strips was determined.

Analysis of experimental research results

Experimentally determined modulus of elasticity of wood during bending of the glued laminated timber beam reinforced with composite strips equals the arithmetic mean value $E_{m,g}$ = 1356.33 kN/cm², as determined by the formula:

$$E_{\mathrm{m,g}} = \frac{l^3\left(P_2 - P_1\right)}{b \cdot h^3\left(w_2 - w_1\right)}\left[\left(\frac{3a}{4l}\right) - \left(\frac{a}{l}\right)^3\right], \tag{1}$$

where: l - distance between supports, cm; b - width of the cross-section, cm; h - height of the cross-section, cm; a - distance between the load point and the nearest support, cm; (P_2 - P_1) - increase in load, kN; (w_2 - w_1) - increase in deformations corresponding to (P_2 - P_1), cm.

The results of the determined vertical deformations from the applied loads to the beam reinforced with composite strips are shown in Figure 2.

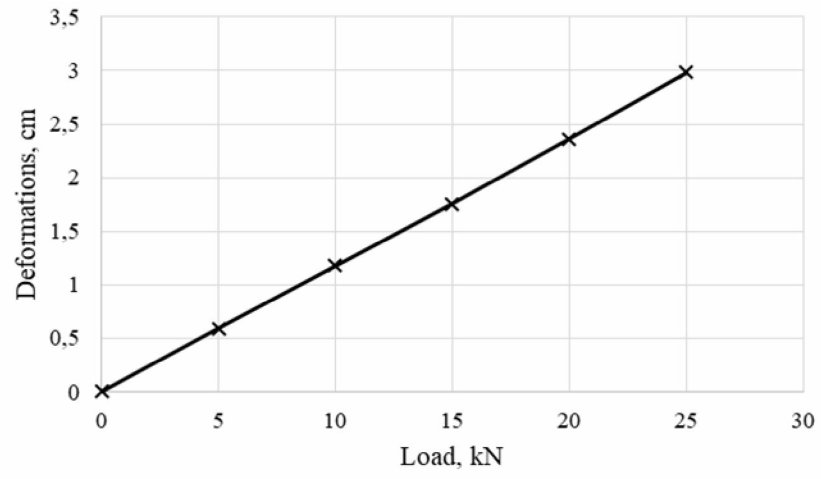


Fig. 2. Graph showing the dependence of vertical deformations on applied loads to the beam reinforced with composite strips

The determination of stresses was performed using the formulas:

$$\sigma_x = E_x \cdot \left(\frac{\varepsilon_x + \nu_{yx} \cdot \varepsilon_y}{1 - \nu_{xy} \cdot \nu_{yx}}\right), \tag{2}$$

$$\sigma_y = E_y \cdot \left(\frac{\varepsilon_y + \nu_{xy} \cdot \varepsilon_x}{1 - \nu_{xy} \cdot \nu_{yx}}\right), \tag{3}$$

$$\tau_{xy} = G \cdot \left[2\varepsilon_{45} - (\varepsilon_x + \varepsilon_y)\right], \tag{4}$$

where: E_x, E_y - moduls of elasticity of wood along and across fibers; ν_{xy}, ν_{yx} - coefficients of transverse deformation of wood (Poisson's ratios); G - shear modulus of wood; $\varepsilon_x, \varepsilon_y, \varepsilon_{45}$ - relative deformations along, across, and at an angle 45° to the wood fibers.

Relative deformations are determined by the formula:

$$\varepsilon_i = \left(\Delta_i - \Delta_0\right) \cdot n, \tag{5}$$

where: $n = 2 \cdot 10^{-6}$ - the price of a division of the deformation gauge "СИИТ-3".

Based on the obtained stress values, diagrams of maximum longitudinal, transverse, and tangential stresses were constructed for the main investigated wood sections (at the center of the span, along the axis of linear loading, and along the support axis) of the experimental sample reinforced with composite strips at a load value of 20 kN, applied along one axis. These diagrams are presented in Figures 3–5.

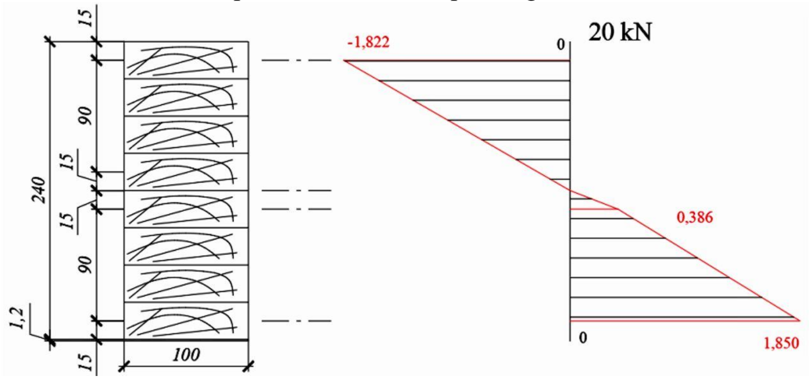
The failure of the experimental sample reinforced with composite strips occurred under a load of 30 kN, applied along one axis, at the section of the loading axis due to one of the initial defects. The general appearance of the experimental sample after the initial signs of strength loss is shown in Figure 6.

To determine the maximum design load per axis of loading, the maximum design resistance of the wood without reinforcement with composite strips was determined according to [12] by the formula:

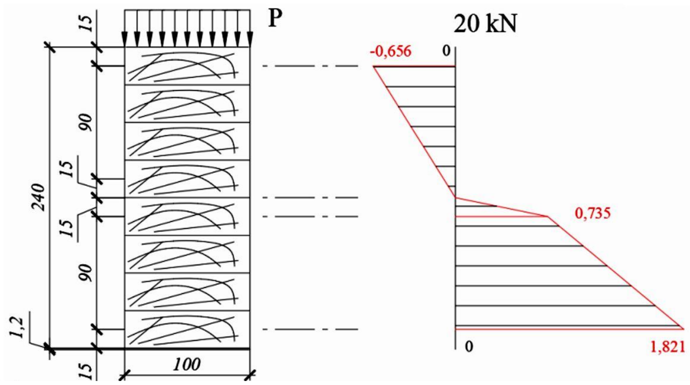
$$f_{m,d} = k_{\text{mod}} \left(f_{m,k} / \gamma_M \right), \tag{6}$$

where: k_{mod} – modification factor for the corresponding service class and load; $f_{m,k}$ – characteristic strength value of wood for the specified strength class under bending; γ_M – reliability coefficient according to the material.

Contours of maximum longitudinal stresses in wood at the center of the span under the corresponding load value



Contours of maximum longitudinal stresses in wood along the axis of applied load at the corresponding load value



Contours of maximum longitudinal stresses in wood along the support axis at the corresponding load value

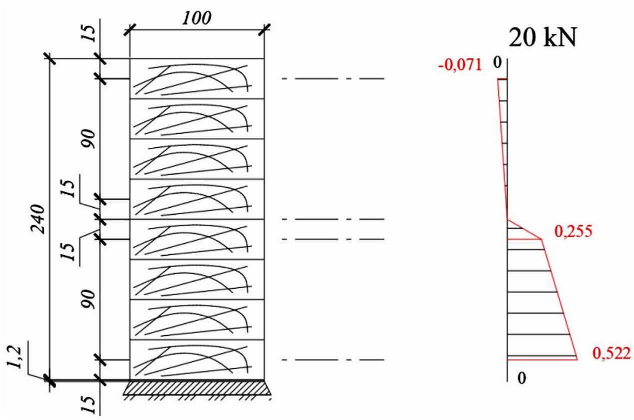


Fig. 3. Maximum longitudinal stresses in the wood of the investigated cross-sections of the experimental sample reinforced with composite strips, at a load value of 20 kN applied along one axis

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Since the k_{mod} coefficient depends on the humidity of the surrounding environment and the duration of loading, it can be disregarded because the experiment was conducted under laboratory conditions, and the loading duration was close to instantaneous.

Contours of maximum transverse stresses along the axis of load application at the corresponding load value

Contours of maximum transverse stresses along the axis of support at the corresponding load value

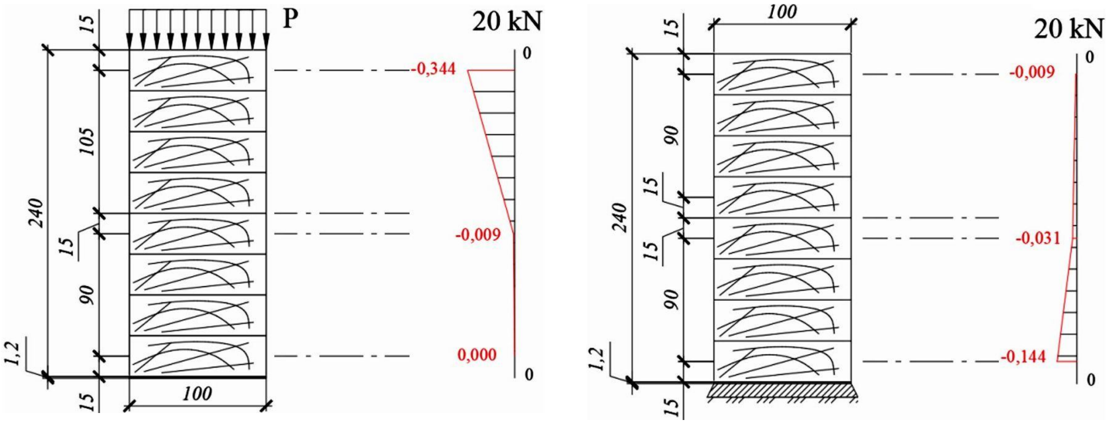

Fig. 4. The maximum transverse stresses in the wood of the investigated cross-sections of the experimental specimen reinforced with composite strips, at a load value of 20 kN, applied to one axis

Contours of maximum shear stresses along the axis of applied load at the corresponding load value

Contours of maximum shear stresses along the support axis at the corresponding load value

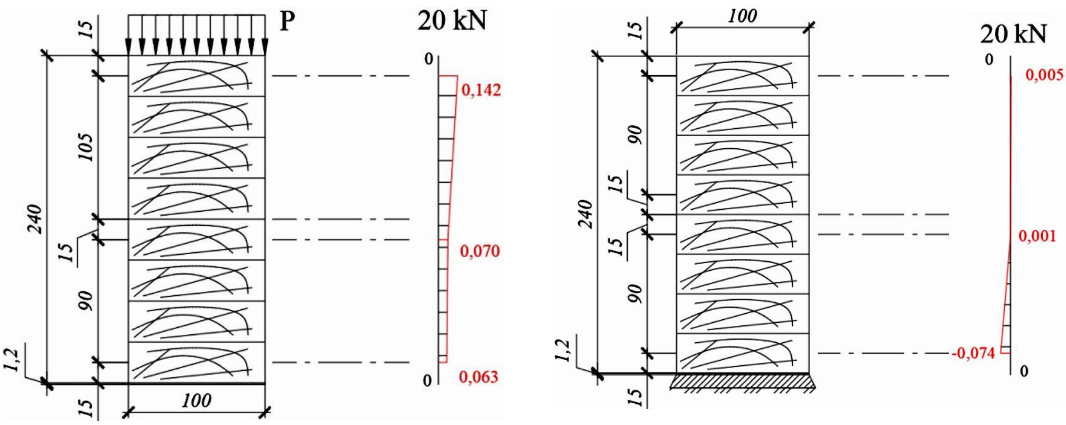

Fig. 5. The maximum shear stresses in the wood of the investigated cross-sections of the experimental sample reinforced with composite strips, at a load value of 20 kN applied to a single axis

As seen from Table 1, the maximum load per axis applied to the experimental sample reinforced with composite strips is 63% higher than the ultimate maximum calculated load without considering the k_{mod} coefficient and 80% higher than the maximum calculated load considering the k_{mod} coefficients for the experimental sample without reinforcement with composite strips.

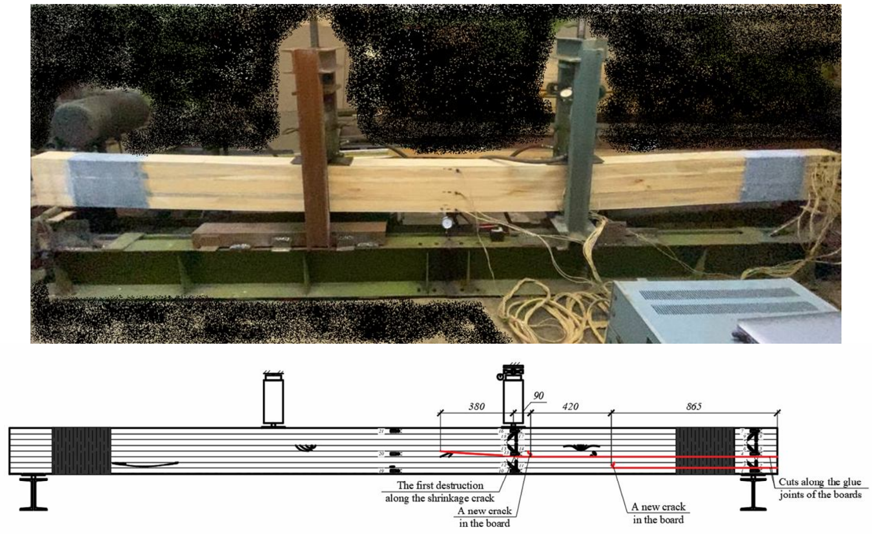

Fig. 6. General view and schematic of the experimental sample after initial signs of strength loss

Table 1

The values of the maximum loads per axis applied to the experimental sample are as follows

Maximum calculated load, kN	Maximum calculated load without considering the utilization coefficient, kN	The maximum load sustained by the sample reinforced with composite strips, kN
16,58	18,43	30

Conclusions

The obtained results can be utilized in conducting research on reinforcing other types of timber structures.

The provided algorithms for conducting experimental research can be applied in studies of other reinforcements of timber structures.

From the graph depicting the dependency of vertical deformations on applied loads to the beam reinforced with composite strips (Figure 2), the linear behavior of the structure can be observed under significant loads applied to a single axis of load application.

It has been experimentally proven that when reinforcing beams made of glued laminated timber with composite strips, there is a redistribution of internal stresses in the calculated sections of the beam. Longitudinal stresses in the tension zone of the beam wood decrease significantly, but normal stresses perpendicular to the fibers and shear stresses increase. Therefore, when reinforcing timber 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 fibers and shear stresses, as well as the combined effect of these stresses.

Based on the results of the experimental study, it has been determined that reinforcing beams made of glued laminated timber with composite strips is an effective method of increasing the load-bearing capacity of the structure, as the actual load at the loss of load-bearing capacity is 63% higher than the calculated value for the unreinforced element.

The obtained experimental results and regularities can be the basis for the development of an engineering methodology for calculating structures made of glued laminated timber reinforced with composite strips.

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ВИЗНАЧЕННЯ НАПРУЖЕНО-ДЕФОРМОВАНОГО СТАНУ БАЛКИ З КЛЕЄНОЇ ДЕРЕВИНИ, ПІДСИЛЕНОЇ КОМПОЗИТНИМИ СТРІЧКАМИ ЕКСПЕРИМЕНТАЛЬНИМ МЕТОДОМ

Актуальність. Тенденція розвитку будівельної галузі в усьому цивілізованому світі вимагає все більше уваги приділяти аспектам екології, а це значить що все більшої популярності набувають матеріали екологічно чисті з мінімальним негативним впливом на навколишнє середовище. В той же час, ці матеріали повинні мати високу міцність і витривалість до різних зовнішніх впливів та навантажень. З цієї позиції найбільшого розповсюдження набувають конструкції з деревини та на її основі. Такі конструкції, виготовлені з відновлювальних природних ресурсів і відзначаються порівняно високою міцністю при відносно низькій щільності, тому і належать до таких матеріалів Балки з клеєної деревини, які є основним конструктивним елементом багатьох будівель і споруд, мають найбільше розповсюдження, саме тому, питання значного збільшення їхньої жорсткості та міцності, завдяки підсиленню їх композитними матеріалами має особливу актуальність. **Мета роботи**. У статті запропоновано методику визначення напружено-деформованого стану балки з клеєної деревини підсиленої 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, також, максимальні поперечні та дотичні напруження по осі прикладання навантаження та по осі опори. Визначено фактичну максимальну несучу здатність експериментальної моделі підсиленої композитними стрічками. **Результати.** Визначено фактичну максимальну несучу здатність експериментальної моделі підсиленої композитними стрічками. Визначено фактичний напружено-деформований стан балки з клеєної деревини підсиленої композитними стрічками.

Ключові слова: електротензоментрія, індикатор годинникового типу, клеєна деревина, конструкції з клеєної деревини, композитні стрічки, напруження, напружено-деформований стан, підсилення композитними стрічками, тензорезистори.

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Комар М.А., Михайловський Д.В. **Визначення напружено-деформованого стану балки з клеєної деревини підсиленої композитними стрічками експериментальним методом** / Опір матеріалів і теорія споруд: наук.-тех. збірн. – К.: КНУБА, 2024. – Вип. 112. – С. 43-51. – Англ.
Запропоновано методику визначення напружено-деформованого стану балки з клеєної деервини підсиленої композитними стрічками експериментальним методом, встановлено фактичний напружено-деформований стан та фактичну несучу здатність такої балки, надано рекомендації щодо аналізу напружено-деформованого стану таких конструкцій в майбутньому.
Табл. 1. Іл. 6. Бібліогр. 16 назв.

УДК 624.011
Komar M.A., Mykhailovskyi D.V. **Definition of the stress-strain state of a glued laminated timber beam reinforced with composite strips using experimental method** / Strength of Materials and Theory of Structures: Scientific-and-technical collected articles. – K.: KNUBA, 2024. – Issue 112. – P. 43-51.
A methodology for determining the stress-strain state of a glued laminated timber beam reinforced with composite strips by experimental method is proposed. The actual stress-strain state and the actual load-bearing capacity of such a beam are determined, and recommendations for analyzing the stress-strain state of such structures in the future are provided.
Tabl. 1. Fig. 6. Ref. 16.

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