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EXPERIMENTAL STUDIES OF PRESTRESSED SOLID TIMBER BEAMS

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Abstract. The article presents the results of comprehensive experimental and theoretical studies on the behavior of timber beams with combined reinforcement, in which both steel and composite reinforcement are simultaneously used. This approach combines the high strength and stiffness of steel with the low weight of composite materials, ensuring rational material use and improved structural efficiency.

Particular attention is given to the development and practical implementation of a method for creating prestressing in composite strip reinforcement located in the tensile zone of the beam. The proposed technique is technologically simple, does not require complex or expensive specialized equipment, and can be implemented both in laboratory conditions and in small- or medium-scale production facilities. The sequence of operations for prestressing the composite reinforcement, anchoring it within the timber base, and fabricating test specimens is described in detail.

The study provides a detailed experimental methodology, including the loading scheme, types of measuring devices, and methods for recording displacements and deformations. The deformation patterns and failure modes of prestressed timber beams with combined reinforcement are identified. Experimental relationships of the “moment–curvature” and “moment–deflection” types are constructed, allowing for quantitative evaluation of the influence of prestressing on the stiffness and strength of the elements.

The research results confirm that introducing prestressing into the composite reinforcement significantly increases the load-bearing capacity and stiffness of timber elements, reduces deflections, and ensures a more uniform stress distribution across the section.

The obtained results have important practical significance and can be applied in the design of new or reconstruction of existing timber structures, particularly in buildings and facilities with large spans, as well as in the development of new design standards, guidelines, and methodological materials for the calculation, manufacturing, and strengthening of timber structures with combined reinforcement.

Keywords: timber beams; combined reinforcement; composite reinforcement; prestressing.

INTRODUCTION

Wood is a modern environmentally friendly material and one of the most in-demand renewable natural resources. Due to its numerous advantages, it has long been used as a construction material.

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Today, solid (unprocessed) timber is rarely used in construction - it has been largely replaced by glued laminated timber (glulam), manufactured using advanced technologies that eliminate the main drawbacks of natural wood.

The application of glulam in large-scale engineering structures, such as halls, bridges, and stadiums, has created the need to enhance its load-bearing capacity in order to reduce cross-sectional height and limit deflections. One of the most effective ways to address this issue is by reinforcing the cross-section with materials of higher strength and stiffness.

ANALYSIS OF PREVIOUS RESEARCH

Under wartime conditions, many authors devote their research to the strengthening of metal [1-3], reinforced concrete [4-5], and timber structures. Researchers have actively investigated the use of various materials - in particular, steel and composite reinforcement - to strengthen timber elements [6–10]. The introduction of stiffer materials into the cross-section contributes to an overall increase in beam stiffness, which, in turn, reduces deflections [11–15]. Experimental results have demonstrated the effectiveness of using composite materials based on synthetic fibers to improve the mechanical performance of timber structures. Advances in the production of fiber-reinforced polymers (FRPs) and the growing availability of synthetic fibers have made composite reinforcement a promising and efficient alternative for strengthening timber elements [16–21]. Current Ukrainian standards [22–25] for wood construction do not provide recommendations for the design and calculation of such elements, making the study of these structures relevant.

Previous studies conducted by the authors [20-21] examined the simultaneous use of steel and composite reinforcement in timber beams, which resulted in a significant increase in stiffness and load-bearing capacity. However, the idea emerged to further enhance the performance of such beams by introducing prestressing into the composite reinforcement located in the tensile zone. The proposed approach does not require complex or specialized equipment and can be implemented sequentially in several simple stages.

Therefore, the aim of this study is to determine the deformation behavior of a timber beam with combined reinforcement, in which the composite strip reinforcement in the tension zone is subjected to prestressing.

PURPOSE AND METHODS

In the laboratory of the Department of Industrial and Civil Engineering at the National University of Water and Environmental Engineering, a prestressed bending element made of solid timber with combined reinforcement was manufactured for the first time.

A known method for prestressing bar reinforcement in the tensile zone during the production of prestressed glued laminated timber beams, which can also be applied to solid timber beams, involves the use of a special collet–clamping mechanism (CCM-1). This mechanism ensures the fixation of reinforcement ends in the beam’s end faces and allows for the application of prestress to both steel and non-metallic bar reinforcement.

However, this technique requires the mandatory use of expensive specialized mechanisms and devices to create the prestressing force, as well as significant labor costs to perform the tensioning process.

The beam models developed using the new prestressing method can be made of either solid or glued laminated timber. In the proposed beams, the main objective is to reduce deflection by introducing prestressing into the composite strip reinforcement. This process is carried out in several simple stages without the use of any complex or costly specialized devices or equipment.

The designed initial deflection in f_1 the timber beam is created by applying an external load, as shown in Fig. 1. The height of the deflection is preliminarily calculated and specified by the designer, and its value is denoted as f_1. In this stressed state, a carbon fiber composite strip Sika CarboDur S-512 with a cross-section of 50 × 1.2 mm is installed in the future tensile zone of the timber element

(Fig. 1). The strip is bonded to the timber surface using Sikadur-30 adhesive. The element is maintained in this prestressed condition for 7 days until the adhesive is fully cured.

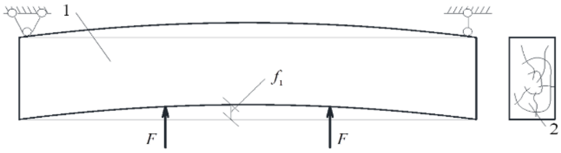

Fig. 1 Creation of the deflection of a bending element to introduce prestressing: 1 – bending timber element; 2 – cross-section of the bending timber element; f_1 – initial curvature of the element; F – concentrated load

Рис. 1 Створення вигину згинального елементу для створення попереднього напруження: 1 – згинальний дерев'яний елемент; 2 – поперечний переріз згинального дерев'яного елементу; f_1 – попередній вигин елемента; F– зосереджена сила

The third stage involves the removal of the concentrated external load F, which was previously applied to create the deflection in the bending timber element. As a result, the timber element reinforced with the carbon fiber strip tends to return to its initial shape. However, this movement is resisted by the bonded Sika CarboDur S-512 carbon strip, which becomes engaged in the work of the structure and counteracts the elimination of the initial deflection (Fig. 2).

Due to this effect, the solid timber bending element reinforced with the Sika CarboDur S-512 strip in the future tensile zone becomes prestressed and retains a residual deflection. In this state, the manufacturing process of the combined prestressed solid timber beam is completed by bonding steel reinforcement in the future compressive zone of the beam. The reinforcement is installed by embedding two Ø12 A500C steel bars into pre-cut grooves and fixing them with a composite mixture of epoxy adhesive and cleaned dry sand (Fig. 3).

After the adhesive mixture has fully cured, the prestressed solid timber beams with combined reinforcement are ready for testing and further structural application.

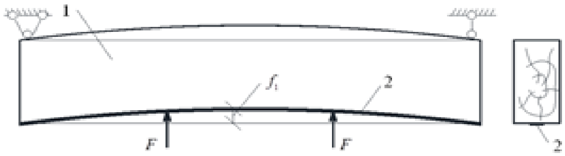

Fig. 2 Bonding of a reinforcing element into the tension zone of a bending timber member: 1 – bending timber element; 2 – reinforcing material; f_1 – initial curvature of the element; F – concentrated load

Рис. 2 Вклеювання армуючого елемента в розтягнуту зону згинального дерев'яного еле-менту: 1 – згинальний дерев'яний елемент; 2 – армуючий матеріал; f_1 – попередній вигин елемента; F– зосереджена сила

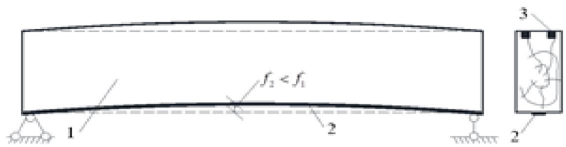

Fig. 3 Bonding of a reinforcing element into the compression zone of a bending timber member: 1 – bending timber element; 2 – reinforcement of the tension zone; 3 – reinforcement of the compression zone; f_1 – deflection of the element; f_2 – residual deflection; F – concentrated load

Рис. 3 Вклеювання армуючого елемента в стиснуту зону згинального дерев'яного елементу: 1 – згинальний дерев'яний елемент; 2 – арматура розтягнутої зони; 3 – арматура стиснутої зони; f_1 – вигин елемента; f_2 – залишковий вигин; F – зосереджена сила

According to this method, two prestressed beam specimens were manufactured, each with a total length of 3 meters and a cross-sectional size of 10 × 15 cm. The beams were reinforced with a carbon fiber strip Sika CarboDur S-512 and steel reinforcement 2Ø12 A500C. The prestressing of the SRB30 (Prst) beam was performed at a load level equal to 30% of the ultimate load, while the SRB45 (Prst) beam was prestressed at 45% of the ultimate load. The value of the ultimate load was determined during the testing of similar unreinforced

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specimens.The process of bonding the carbon fiber strip under load is shown in Figure 4

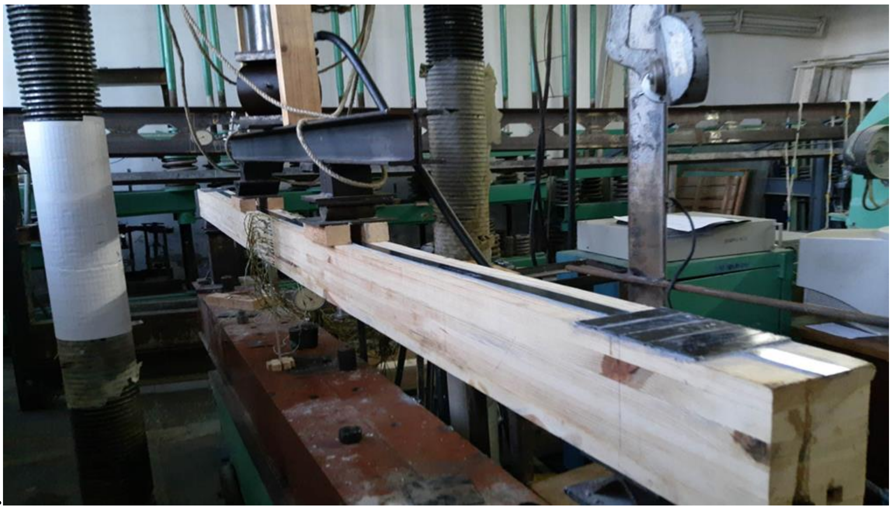

Fig. 4 The curing process of the adhesive when bonding the composite strip reinforcement Sika CarboDur S-512 to the timber beam. Photo by Gomon, 2022
Рис. 4 Процес твердіння клею при приклеюванні композитної стрічкової арматури Sika CarboDur S-512 до деревини балки. Фото П. Гомон, 2022

EXPERIMENTAL STUDIES TEST SETUP

The manufactured and prepared beams made of solid and glued timber, as well as those with passive and prestressed combined reinforcement, were installed in the testing setup on hinged movable and fixed supports. In this position, all necessary measuring instruments were mounted and fixed, allowing the measurement of deflections, relative deformations of the timber in different layers along the beam height, and control of the composite action between the reinforcement and the timber.

The structural model corresponded to a simply supported beam subjected to two concentrated loads, each applied at a certain distance from the supports (four-point bending of flexural elements) (Fig. 5), in accordance with the recommendations EN 408:2007 [24].

Dial indicators ИЧ-10m were installed on the supports to measure the deformation resulting from the settlement of the beam supports under loading. A deflectometer model 6-PAO was positioned at midspan to record beam deflection.

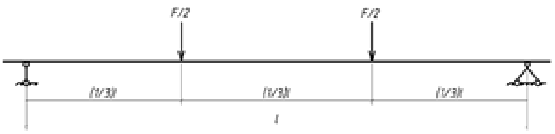

Fig. 5 Timber beam scheme for calculations
Рис. 5 Розрахункова схема дерев’яних балок

To measure possible slippage deformations of the steel reinforcement bars and the composite carbon fiber strip reinforcement Sika CarboDur S-512, dial-type indicators ИЧ-10n were mounted at the beam ends. All instruments were fixed on specially designed holders placed at predetermined points along the beam’s cross-section (Fig. 6).

Before testing each specimen, its geometrical dimensions were verified, and the initial readings from all instruments were recorded in the experimental testing logbook. The instruments used during the experimental investigations had previously undergone official state calibration.

The prestressed solid timber beams with combined reinforcement, after verifying their geometrical dimensions, were installed in the testing setup. Subsequently, all necessary instruments were mounted and adjusted to their operational condition.

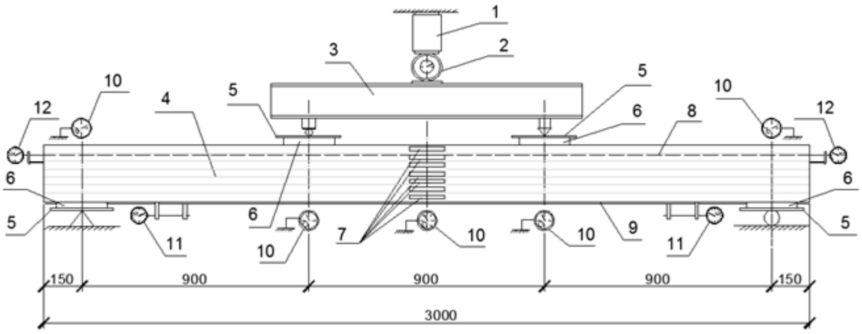

Fig. 6 Test setup scheme for bending tests of timber beams: 1) jack; 2) dynamometer; 3) steel crosshead; 4) tested beam; 5) steel pad; 6) wooden pad; 7) strain gauges; 8) steel reinforcement 2 Ø A500C; 9) composite strip reinforcement Sika CarboDur S-512; 10) deflectometer 6-PAO; 11) indicator ICh-10n; 12) indicator ICh-10n

Рис. 6 Схема дослідної установки для випробування дерев'яних балок на згин: 1) домкрат; 2) динамометр; 3) металева траверса; 4) досліджувана балка; 5) металева підкладка; 6) дерев'яна підкладка; 7) тензодатчики; 8) сталева арматура 2 Ø А500С; 9) композитна стрічкова арматура Sika CarboDur S-512; 10) прогиномір 6-ПАО; 11) індикатор ИЧ-10н; 12) індикатор ИЧ-10н

The loading was applied incrementally in steps of 500–1000 N, using a hydraulic jack model DOSM-5. After each successive loading step, a pause of up to 5 minutes was made to record readings from the dial indicators, deflectometer, and strain gauges. All obtained data were recorded in the test logbook.

When the applied load reached over 90% of the expected ultimate load, the measuring instruments were removed to prevent possible damage in case of sudden failure of the tested specimens.

RESEARCH RESULTS

Stage of Prestressing Creation. The ultimate bending moment for the unreinforced beam was determined as $M_{\max} = 19{,}98 kN/m$. The prestressing level used to create the initial deflection was set for the combined reinforced beam SBR30 (Prst) at $M_{\max} = 6{,}0 kN/m$, and for the beam SBR45 (Prst) at $M_{\max} = 9{,}0 kN/m$, corresponding to 30% and 45% of the maximum load sustained by the unreinforced timber beam SB, respectively.

The behavior of the normal cross-sections can be illustrated using moment–curvature diagrams (Fig. 7, Fig. 8).

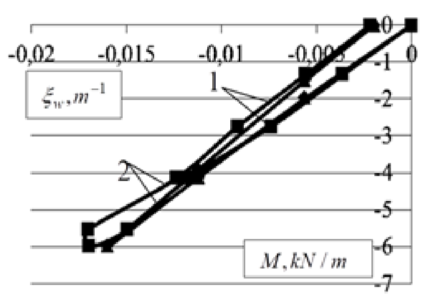

Fig. 7 Experimental (1) and theoretical (2) "moment –curvature" graphs during loading and unloading of the SBR30(Prst) beam

Рис. 7 Експериментальний (1) та теоретичний (2) графіки «момент-кривина» при завантаженні та розвантаженні балки SBR30(Prst)

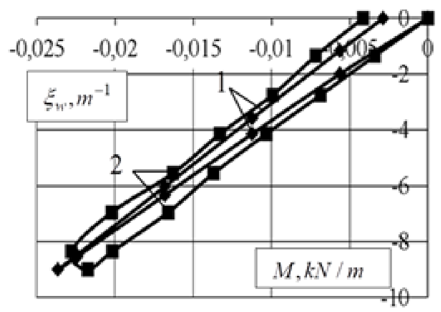

Fig. 8 Experimental (1) and theoretical (2) "moment – curvature" graphs during loading and unloading of the SBR30(Prst) beam

Рис. 8 Експериментальний (1) та теоретич-ний (2) графіки «момент-кривина» при за-вантаженні та розвантаженні балки SBR45(Prst)

The curvatures in the midspan cross-section were calculated during the loading of the SBR30 and SBR45 beams under prestressing. The curvatures of the SBR30 and SBR45 beams at the time of bonding the composite strip were $\xi_{SBR30,Prst} = -0{,}017m^{-1}$ and, $\xi_{SBR45,Prst} = -0{,}017m^{-1}$ respectively.

As shown in Fig. 7 and Fig. 8, after bonding the carbon fiber composite strip, the beam was unloaded, and the calculated model of the normal cross-section was modified to account for the addition of the carbon strip. During the first 2–3 stages of unloading, typical changes for timber are observed, indicating wood relaxation. At subsequent unloading stages, the curvature stabilizes and reaches the predicted level.

As a result of the bonded carbon fiber composite strip added to the bottom (tensile) zone, a residual deflection remains after unloading, at which the external force equals zero. The residual curvature in the SBR30 (Prst) and SBR45 (Prst) beams is

$\xi_{SBR30,0} = -0{,}0022m^{-1}$ and,

$\xi_{SBR30,0} = -0{,}0042m^{-1}$ respectively.

Subsequently, two Ø12 mm A500C steel reinforcement bars were bonded into the grooves of the future compressive zone of the SBR30 (Prst) and SBR45 (Prst) beams.

Stage of Testing the Prestressed Beam. After completing all operations for creating the prestress in the solid timber element with combined reinforcement and following the full curing of the adhesive, experimental testing of the prestressed beams SBR30 (Prst) and SBR45 (Prst) was carried out.

The results of the experimental tests were recorded in the test logbook and, after processing, are presented in Fig. 9 for the SBR30 (Prst) beam and Fig. 10 for the SBR45 (Prst) beam.

The prestressed timber beam with combined reinforcement, which was prestressed to a 0.3 load level, failed completely due to fiber rupture in the tensile zone of the timber. The failure of the second beam occurred through timber splitting along the grain. This indicates that the influence of shear stresses in prestressed combined reinforced solid timber beams is extremely significant, and therefore, a methodology for strengthening inclined cross-sections of such elements should be developed in the future.

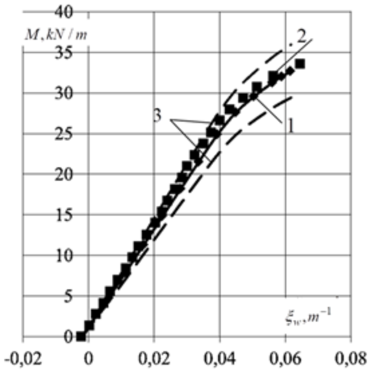

Fig. 9 Theoretical (1) and experimental (2) curvature values depending on the applied load in the midspan section of the SBR30(Prst) beam with prestressed combined reinforcement, with deviation limits from –10% to +10% (3) of the established theoretical bending moment value

Рис. 9 Теоретичні (1) та експериментальні значення (2) кривини в залежності від прикладеного навантаження в серед-ньому перерізі балки SBR30(Prst) з попередньо напруженим комбінова-ним армуванням з межами відхилень від -10% до +10% (3) від вста-новленого теоретичного значення згинального моменту

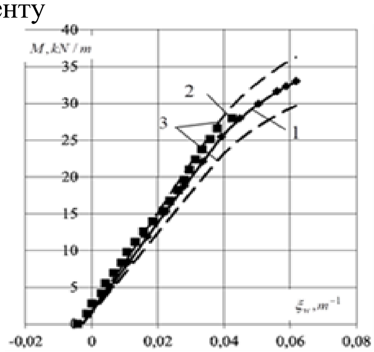

Fig. 10 Theoretical (1) and experimental (2) curvature values depending on the applied load in the midspan section of the prestressed combined reinforced beam SBR45(Prst) (3 – range of experimental data distribution ±10%)

Рис. 10 Теоретичні (1) та експериментальні значення (2) кривини в залежності від прикладеного навантаження в середньому перерізі попередньо напруженої комбіновано армованої балки SBR45(Prst) (3 – межі розподілу експериментальних значень ±10%)

The deflection–moment growth diagrams for solid timber beams are shown in Fig. 11: unreinforced beams – SB, solid timber beams with passive combined reinforcement – SBR, prestressed combined reinforced solid timber beams – SBR30 (Prst), and prestressed combined reinforced solid timber beams – SBR45 (Prst).

As a result of the study, it was established that the ultimate moment according to the second limit state, which is determined based on the ultimate deflection of the element in the tested solid timber beam, increases with the addition of reinforcement in both the compressive and tensile zones. It was also found that the creation of prestressing in the composite reinforcement of the tensile zone further increases the ultimate moment corresponding to the beam's deflection limits.

An increase in the initial curvature, which arises due to higher levels of prestressing, additionally enhances the ultimate moment according to the second limit state. The effect of increasing prestress is significant; however, it is critical not to exceed the service-level deflections of the unreinforced solid timber flexural element when applying prestress to the Sika CarboDur S-512 carbon strip.

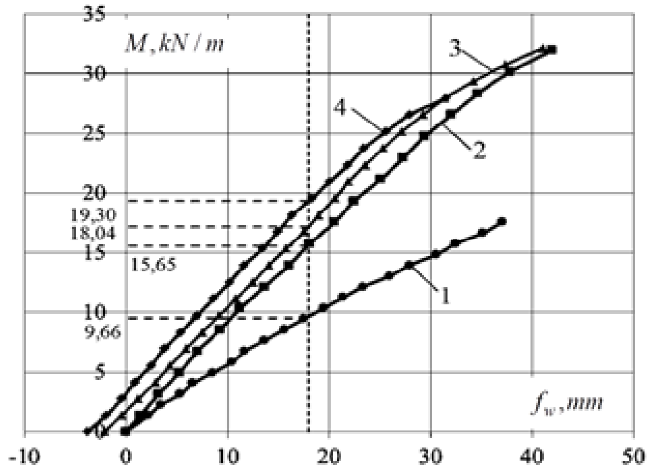

Fig. 11 Deflection–moment diagrams for solid timber beams with graphical determination of the ultimate deflection for: 1 – SB; 2 – SBR; 3 – SBR30(Prst); 4 – SBR45(Prst)

Рис. 11 Діаграми прогинів від зростання моментів для балок з цільної деревини з графічним встановленням граничного прогину для: 1 – SB; 2 – SBR; 3 - SBR30(Prst); 4 - SBR45(Prst)

CONCLUSIONS AND RECOMMENDATIONS

Enhancement of the load-bearing capacity and stiffness of timber beams with combined reinforcement: The introduction of steel and composite reinforcement, as well as the application of prestressing in the composite strip, significantly increases the stiffness and load-bearing capacity of timber beams, reducing deflections and ensuring a more uniform stress distribution across the cross-section.

Effectiveness of prestressing the composite reinforcement: Creating prestress in the Sika CarboDur S-512 carbon fiber strip in the tensile zone provides residual deflection and increases the ultimate moment, allowing improved beam performance under high loads without the need for additional complex devices.

Failure characteristics: Prestressed beams with combined reinforcement exhibit different failure mechanisms: at lower levels of prestress, failure occurs through timber fiber rupture in the tensile zone, while at higher levels, splitting along the grain is observed. This indicates a significant influence of shear stresses and highlights the need for further research to strengthen inclined cross-sections.

Practical application and recommendations: The results of the study can be used for the design of new and the reconstruction of existing timber structures with large spans, as well as for the development of methodologies, regulatory documents, and guidelines regarding the reinforcement and prestressing of timber beams.

REFERENCES

1. **Hlitin O., Bilyk S., Radetskyi S., Sonko O., Kravchenko O.** (2024). An effective method for strengthening steel beams and purlins using an elastic support in the span. *Building Constructions. Theory and Practice,. (15),174-184.* [in Ukrainian] https://doi.org/10.32347/2522-4182.15.2024.174-184
2. **Rudnieva I. V.** (2021) Technological features of strengthening steel structures by bonding high-strength fiber-reinforced systems during reconstruction. *Building Constructions. Theory and Practice,.(8), 25-31.* [in Ukrainian] https://doi.org/10.32347/2522-4182.8.2021.32-43
3. **Hetun H., Koliakova V., Bezklyubenko I., Solomin A.** (2023) Structural solutions for blast-resistant buildings with civil protection premises. *Building Constructions. Theory and Practice,. (13), 41-50.* [in Ukrainian] https://doi.org/10.32347/2522-4182.13.2023.41-50
4. **Zhuravskyi O. D., Tymoshchuk V. A.** (2020) Calculation model of flat reinforced concrete slabs strengthened with external prestressed reinforcement. *Building Constructions. Theory and Practice,. (7), 4-11.* [in Ukrainian] https://doi.org/10.32347/2522-4182.1.2017.193-198
5. **Rudnieva I., Priadko M., Priadko H.** (2020) Features and prospects of using FRP composite technologies for strengthening building structures during reconstruction. *Building Constructions. Theory and Practice. (7), 12-22.* [in Ukrainian] https://doi.org/10.32347/2522-4182.7.2020.12-22
6. **Demchyna B. H., Surmai M. I., Kravz A. R., Bliakhar T. I.** (2010) Experience in manufacturing glued-laminated timber beams reinforced with non-metallic reinforcement. *Modern Building Materials, Structures, and Innovative Construction Technologies: Bulletin DonNABA. № 5 (85). T. II. Makiyivka: DonNABA, 193-197.* [in Ukrainian]
7. **Yermolenko D. A., Ishchenko M. S.** (2017) Strength and deformability of glued timber beams reinforced with polymer mesh. *ACADEMIC JOURNAL Series: Industrial Machine Building, Civil Engineering. — Poltava: PNTU. T. 2 (47). S. 140-147.* [in Ukrainian]
8. **Mirski R., Kuli'nski M., Dziurka D., Thomas M., Antonowicz R**. (2012) Strength properties of structural glulam elements from pine (Pinus sylvestris L.) Timber reinforced in the tensile zone with steel and basalt rods. *Materials. Vol. 14(10), Article number 2574.* https://doi.org/10.3390/ma14102574
9. **Borri A., Corradi M., Grazini A.** (2005) A method for flexural reinforcement of old wood beams with CFRP materials *Composites. Vol. 36. Pp. 143–153.* https://doi.org/10.1016/j.compositesb.2004.04.013
10. **Andor, K., Lengyel, A., Polgár, R., Fodor, T., & Karácsonyi, Z.** (2015). Experimental and statistical analysis of spruce timber beams reinforced with CFRP fabric. *Construction and Building Materials, 99, 200–207.* https://doi.org/10.1016/j.conbuildmat.2015.09.026
11. **Corradi M., Osofero A. I., Borri A. (2019)** Repair and reinforcement of historic timber structures with stainless steel — a review *Metals. Vol. 9(1). Article 106.* https://doi.org/10.3390/met9010106
12. **Soriano J., Pellis B. P., Mascia N. T.** (2016) Mechanical performance of glued-laminated timber beams symmetrically reinforced with steel bars. *Composite Structures. Vol. 150.* https://doi.org/10.1016/j.compstruct.2016.05.016
13. **Usman A., Sugiri S.** (2015) Analysis of the Strength of Timber and Glulam Timber Beams with Steel Reinforcement. *Journal of Engineering and Technological Sciences. Vol. 47. Pp. 601-611.* https://doi.org/10.5614/j.eng.technol.sci.2015.47.6.1
14. **De Luca V., Marano C.** (2012) Prestressed glulam timbers reinforced with steel bars. *Construction and Building Materials. Vol. 30. Pp. 206-217.* https://doi.org/10.1016/j.conbuildmat.2011.11.016
15. **Alam P., Ansell M.P., Smedley D.** Mecha-nical repair of timber beams fractured in flexure using bonded-in reinforcements. *Compos B Eng, 2009. Vol. 40 (2). Pp. 95-106.* https://doi.org/10.1016/j.compositesb.2008.11.010
16. **Raftery G.M. , Whelan C.** (2014) Low-grade glued laminated timber beams reinforced using improved arrangements of bonded-in GFRP rods. *Constr Build. Mater. Vol. 52. Pp. 209-220.*

https://doi.org/10.1016/j.conbuildmat.2013.11.044

17. **Gómez E.P., González M.N., Hosokawa K., Cobo A.** (2019) Experimental study of the flexural behavior of timber beams reinforced with different kinds of FRP and metallic fibers. *Compos Struct. (213), 308-316.* https://doi.org/10.1016/j.compstruct.2019.01.099
18. **Wdowiak A., Brol J.** (2019) Effectiveness of reinforcing bent non-uniform pre-stressed glulam beams with basalt fibre reinforced. *Polymers Rods. Materials. (12). Article number 3141.* https://doi.org/10.3390/ma12193141
19. **Kliger R., Haghani R., Brunner M., Harte A. M., Schober K-U.** (2016) Wood-based beams strengthened with FRP laminates: improved performance with pre-stressed systems. *Eur. J. Wood Prod. (74), 319–330.* https://doi.org/10.1007/s00107-015-0970-5
20. **Mykhailovskyi D., Komar M.** (2023) Analysis of studies on the use of composite strips for strengthening timber structures] *Budivelni konstruktsii. Teoriia i praktyka. (10),. 4-10.* [in Ukrainian] https://doi.org/10.32347/2522-4182.10.2022.4-10
21. **Mykhailovskyi D. V., Komar M. A.** (2021) Reinforcement of timber structures with composite materials: current state and prospects *Building Constructions. Theory and Practice (9), 72-80.* [in Ukrainian] https://doi.org/10.32347/2522-4182.9.2021.72-80
22. **DSTU-N B V.2.6-184:2012** "Konstruktsii z tsilnoi i kleienoi derevyny. Nastanova z proektuvannia" [Structures made of solid and glued timber. Design guidelines] [*chynnyi vid 01.04.2013*] *Kyiv, "Ukrarkhbudinform", 2013. 120 s.* [in Ukrainian]
23. **DBN V.2.6-161:2017** "Dereviani konstruktsii. Osnovni polozhennia" [Timber structures. Basic provisions] [*chynnyi vid 01.04.2017*] *Kyiv, "Ukrarkhbudinform", 2017. 111 s.* [in Ukrainian]
24. **DSTU EN 408:2012** "Konstruktsii dereviani. Konstruktsiina derevyna ta kleiena laminovana derevyna. Vyznachennia deiakykh fizychnykh ta mekhanichnykh vlastostei" (EN 408:2003, IDT) [Timber structures. Structural timber and glued laminated timber. Determination of certain physical and mechanical properties] [*chynnyi vid 04.02.2013*] *Kyiv: Minrehion Ukrainy, 2013. 42 s.* [in Ukrainian]
25. **DSTU EN 408:2007** "Lisomaterialy konstruktsiini. Konstruktsiina ta kleiena sharuvata derevyna. Vyznachennia deiakykh fizychnykh ta mekhanichnykh vlasnostei" [Structural timber. Structural and glued laminated timber. Determination of certain physical and mechanical properties]] [*chynnyi vid 10.10.2007*] *Kyiv: Derzhspozhystandart Ukrainy, 2012.* [in Ukrainian]

LITERATURE

1. **Hlitin O., Bilyk S., Radetskyi S., Sonko O., Kravchenko O.** (2024). Efektyvnyi sposib pidsylennia metalevykh balok i prohoniv za dopomohoiu pruzhnoi opory v proloti. *Budivelni konstruktsii. Teoriia i praktyka. (15),174-184.* https://doi.org/10.32347/2522-4182.15.2024.174-184
2. **Rudnieva I. V.** (2021) Tekhnolohichni osoblyvosti pidsylennia metalievykh konstruktsii metodom nakleiuvannia vysokomitsnykh fibroarmovanykh system pry rekonstruktsii *Budivelni konstruktsii. Teoriia i praktyka. (8), 25-31.* https://doi.org/10.32347/2522-4182.8.2021.32-43
3. **Hetun H., Koliakova V., Bezklyubenko I., Solomin A.** (2023) Konstruktyvni rishennia vybukhostiikykh budivel z prymishchennaiamy tsyvilnoho zakhystu naselennia *Budivelni konstruktsii. Teoriia i praktyka. (13), 41-50.* https://doi.org/10.32347/2522-4182.13.2023.41-50
4. **Zhuravskyi O. D., Tymoshchuk V. A.** (2020) Rozrakhunkova model ploskikh zalizobetonnykh plyt, pidsilenykh zovnishnoiu napruzhenoiu armaturoiu *Budivelni konstruktsii. Teoriia i praktyka. (7), 4-11.* https://doi.org/10.32347/2522-4182.1.2017.193-198
5. **Rudnieva I., Priadko M., Priadko H.** (2020) Osoblyvosti ta perspektyvy vykorystannia tekhnolohii pidsylennia budivelnykh konstruktsii kompozytsiynymy FRP-materialamy pry rekonstruktsii sporud *Budivelni konstruktsii. Teoriia i praktyka.(7), 12-22.* https://doi.org/10.32347/2522-4182.7.2020.12-22
6. **Demchyna B. H., Surmai M. I., Kravz A. R., Bliakhar T. I.** (2010) Dosvid vyhotovlennia doshatokleienykh balk armovanykh nemetalevoiu armaturoiu. *Suchasni budivelni materialy, konstruktsii ta innovatsiyni tekhnolohii*

zvedennia budivel i sporud: Visnyk DonNABA. № 5 (85). T. II. Makiyivka: DonNABA. S. 193-197.

7. **Yermolenko D. A., Ishchenko M. S.** (2017) Mitsnist ta deformatyvnist kleienykh derevianykh balk, armovanykh polimernoiu sitkoiu *ACADEMIC JOURNAL Series: Industrial Machine Building, Civil Engineering. — Poltava: PNTU. T. 2 (47). S. 140-147.* http://orcid.org/0000-0001-6690-238X
8. **Mirski R., Kuli'nski M., Dziurka D., Thomas M., Antonowicz R**. (2012) Strength properties of structural glulam elements from pine (Pinus sylvestris L.) Timber reinforced in the tensile zone with steel and basalt rods. *Materials. Vol. 14(10), Article number 2574.* https://doi.org/10.3390/ma14102574
9. **Borri A., Corradi M., Grazini A.** (2005) A method for flexural reinforcement of old wood beams with CFRP materials *Composites. Vol. 36. Pp. 143–153.* https://doi.org/10.1016/j.compositesb.2004.04.013
10. **Andor, K., Lengyel, A., Polgár, R., Fodor, T., & Karácsonyi, Z.** (2015). Experimental and statistical analysis of spruce timber beams reinforced with CFRP fabric. *Construction and Building Materials, 99, 200–207.* https://doi.org/10.1016/j.conbuildmat.2015.09.026
11. **Corradi M., Osofero A. I., Borri A. (2019)** Repair and reinforcement of historic timber structures with stainless steel — a review *Metals. Vol. 9(1). Article 106.* https://doi.org/10.3390/met9010106
12. **Soriano J., Pellis B. P., Mascia N. T.** (2016) Mechanical performance of glued-laminated timber beams symmetrically reinforced with steel bars. *Composite Structures. Vol. 150.* https://doi.org/10.1016/j.compstruct.2016.05.016
13. **Usman A., Sugiri S.** (2015) Analysis of the Strength of Timber and Glulam Timber Beams with Steel Reinforcement. *Journal of Engineering and Technological Sciences. Vol. 47. Pp. 601-611.* https://doi.org/10.5614/j.eng.technol.sci.2015.47.6.1
14. **De Luca V., Marano C.** (2012) Prestressed glulam timbers reinforced with steel bars. *Construction and Building Materials. Vol. 30. Pp. 206-217.* https://doi.org/10.1016/j.conbuildmat.2011.11.016
15. **Alam P., Ansell M.P., Smedley D.**. Mechanical repair of timber beams fractured in flexure using bonded-in reinforcements. *Compos B Eng, 2009. Vol. 40 (2). Pp. 95-106.* https://doi.org/10.1016/j.compositesb.2008.11.010
16. **Raftery G.M. , Whelan C.** (2014) Low-grade glued laminated timber beams reinforced using improved arrangements of bonded-in GFRP rods. *Constr Build. Mater. Vol. 52. Pp. 209-220.* https://doi.org/10.1016/j.conbuildmat.2013.11.044
17. **Gómez E.P., González M.N., Hosokawa K., Cobo A.** (2019). Experimental study of the flexural behavior of timber beams reinforced with different kinds of FRP and metallic fibers. *Compos Struct.(213), 308-316.* https://doi.org/10.1016/j.compstruct.2019.01.099
18. **Wdowiak A., Brol J.** (2019) Effectiveness of reinforcing bent non-uniform pre-stressed glulam beams with basalt fibre reinforced. *Polymers Rods. Materials. (12). Article number 3141.* https://doi.org/10.3390/ma12193141
19. **Kliger R., Haghani R., Brunner M., Harte A. M., Schober K-U.** (2016) Wood-based beams strengthened with FRP laminates: improved performance with pre-stressed systems. *Eur. J. Wood Prod. Vol. 74. Pp. 319–330.* https://doi.org/10.1007/s00107-015-0970-5
20. **Mykhailovskyi D., Komar M.** (2022) Analiz doslidzhen zastosuvannia kompozytnykh strichok dlia pidsylennia derevianykh konstruktsii *Budivelni konstruktsii. Teoriia i praktyka. (10),. 4-10.* https://doi.org/10.32347/2522-4182.10.2022.4-10
21. **Mykhailovskyi D. V., Komar M. A.** (2021) Armuvannia konstruktsii z derevyny kompozytnymy materialamy: stan i perspektyvy *Budivelni konstruktsii. Teoriia i praktyka.(9), 72-80.* https://doi.org/10.32347/2522-4182.9.2021.72-80
22. **DSTU-N B V.2.6-184:2012** Konstruktsii z tsilnoi i kleienoi derevyny. Nastanova z proektuvannia [*chynnyi vid 01.04.2013*] *Kyiv, "Ukrarkhbudinform", 2013. 120 s.*
23. **DBN V.2.6-161:2017** Dereviani konstruktsii. Osnovni polozhennia [*chynnyi vid 01.04.2017*] *Kyiv, "Ukrarkhbudinform", 2017. 111 s.*
24. **DSTU EN 408:2012** Konstruktsii dereviani. Konstruktsiina derevyna ta kleiena laminovana derevyna. Vyznachennia deiakykh fizychnykh ta

mekhanichnykh vlasnostei (EN 408:2003, IDT) [*chynnyi vid 04.02.2013*] *Kyiv: Minrehion Ukrainy, 2013. 42 s.*

25. **DSTU EN 408:2007** Lisomaterialy konstruktsiini. Konstruktsiina ta kleiena sharuvata derevyna. Vyznachennia deiakykh fizychnykh ta mekhanichnykh vlasnostei [*chynnyi vid 10.10.2007*] *Kyiv: Derzh-spozhystandart Ukrainy, 2012.*

ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ ПОПЕРЕДНЬО НАПРУЖЕНИХ ДЕРЕВ'ЯНИХ БАЛОК ІЗ ЦІЛЬНОЇ ДЕРЕВИНИ

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Анотація. У статті наведено результати комплексних експериментальних і теоретичних досліджень роботи дерев'яних балок із комбінованим армуванням, у яких одночасно використано сталеву та композитну арматуру. Такий підхід дозволяє поєднати високу міцність і жорсткість сталі з малою вагою композитних матеріалів, що забезпечує раціональне використання матеріалів і підвищення ефективності конструкції.

Основна увага приділена розробленню та практичній реалізації методу створення попереднього напруження в композитній стрічковій арматурі, розташованій у розтягнутій зоні балки. Запропонований спосіб є технологічно простим, не потребує використання складного або дорогого спеціалізованого обладнання, може бути реалізований у лабораторних умовах і на підприємствах малої та середньої потужності. Описано послідовність виконання операцій із попереднього натягування композитної арматури, фіксації її в дерев'яній основі та подальшого виготовлення зразків для випробувань.

У роботі детально представлено методику проведення експериментальних досліджень, включно з описом схеми навантаження, типів вимірювального обладнання, способів фіксації переміщень і деформацій. Визначено закономірності деформування та встановлено особливості руйнування попередньо напружених комбіновано армованих дерев'яних балок. Побудовано експериментальні залежності типу «момент–кривина» та «момент–прогин», які дозволяють кількісно оцінити вплив попе-реднього напруження на жорсткість і міцність елементів.

Результати досліджень підтвердили, що введення попереднього напруження в композитній арматурі суттєво підвищує несучу здатність та жорсткість дерев'яних елементів, зменшує прогини та забезпечує більш рівномірний розподіл напружень у перерізі.

Отримані результати мають важливе практичне значення та можуть бути використані при проєктуванні нових і реконструкції існуючих дерев'яних конструкцій, особливо в будівлях і спорудах із великими прольотами, а також при розробленні нових нормативних документів, рекомендацій і методичних матеріалів щодо розрахунку, виготовлення та підсилення дерев'яних конструкцій із комбінованим армуванням.

Ключові слова: дерев'яні балки; комбіноване армування; композитна арматура; попереднє напруження.

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