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Analysis of the stress-strain state of laminated timber beams reinforced with composite tapes

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The use of timber structures is gaining popularity around the world. The main laminated timber constructions are beams, the study of which has received much attention. To increase rigidity and strength, beam structures are reinforced. There are many different methods of reinforcing such structures (steel reinforcement, plates, composite reinforcement, etc.). The least researched one of them is reinforcement with composite tapes. For a further detailed analysis of the stress-strain state of laminated timber elements of rectangular cross-section reinforced with composite tapes, a number of numerical researches were performed using the finite element method in the LIRA-CAD software package using three-dimensional and flat finite elements, taking into account the features of work and structure of laminated timber beams and carbon fiber composite tapes. Therefore, according to the conducted research, this method of reinforcement can be considered effective.

Keywords: composite materials, composite tapes, laminated timber construction, timber construction, reinforcement, strengthening.

Аналіз напружено-деформованого стану балок з клеєної деревини, підсилених композитними стрічками

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Використання дерев'яних конструкцій в усьому світі набуває популярності. Досвід впровадження таких конструкцій особливо конструкцій з клеєної деревини (ККД) доводить, що їхнє використання є доцільним. Основними, дослідженням яких приділено чимало уваги, конструкціями з клеєної деревини є балки. Для збільшення жорсткості та підвищення міцності балочних конструкцій з ККД запропоновано виконувати їх армування. Є багато різних методів армування таких конструкцій (сталевою арматурою, пластинами, композитною арматурою тощо). Найменш досліджений з них це армування композитними стрічками. Для подальшого, детального аналізу напружено-деформованого стану елементів з клеєної деревини прямокутного перерізу армованого композитними стрічками проведено ряд чисельних досліджень за допомогою методу скінченних елементів в програмному комплексі ЛІРА-САПР із використанням об'ємних та плоских скінченних елементів, враховуючи особливості роботи та фізико-механічні властивості клеєної деревини та композитних стрічок із вуглецевих волокон, а саме було обрано балки прямокутного поперечного перерізу склеєні з дошок одного класу міцності змодельовані об'ємними СЕ №36 з армуванням композитними стрічками змодельованими плоскими СЕ №44 та без нього на двох шарнірних опорах, завантажені рівномірно розподіленим навантаженням різної інтенсивності та Spanів. Після проведеного розрахунку можна зазначити, що армовані балки в середньому на 18% менші вертикальні деформації та на 27% менші нормальні напруження від аналогічних балок не армованих композитними стрічками. Та після аналізу прикладання різних рівномірних навантажень можна зазначити, що при збільшенні навантаження практично не змінюється відсоткова різниця між значеннями прогинів та максимальних нормальних напружень таких балок. За результатами проведених досліджень запропонований метод армування можна вважати ефективним.

Ключові слова: композитні матеріали, конструкція з клеєної деревини, дерев'яна конструкція, підсилення, армування, композитна стрічка.

Introduction

The use of timber structures is gaining popularity all over the world. The experience of implementing such constructions, especially laminated constructions (LTC) proves that their use is expedient. Beams are the main LTCs, the research of which has received maximum attention. In order to increase the rigidity and strength of beam structures with efficiency, it is suggested to perform their reinforcement. There are many different methods of reinforcing such structures (steel reinforcement, plates, composite reinforcement, etc.). The least researched one of them is reinforcement with composite tapes.

For a further detailed analysis of the stress-strain state of elements made of timber with a rectangular cross-section reinforced with composite tapes, a number of numerical researches were carried out using the finite element method (FEM) in the LIRA-CAD program complex (PC) using volumetric and flat finite elements (FEM), taking into account the features of work and the structure of beams made of laminated timber and composite tapes of carbon fibers.

Review of the research sources and publications

Based on the analysis of scientific sources of research and publications [1], it was established that there is very little and extremely insufficient research on the strengthening of timber structures and, in particular, beams made of laminated timber reinforced with composite tapes. In particular, this research, the results of which are given in the article [2] by the authors S. Gomon and M. Polishchuk, in which they experimentally consider the technology of manufacturing laminated timber beams reinforced with rod reinforcement and composite tapes. Also, certain research results are described in the article [3] by the authors Bashynskyi O., Bondarchuk T., Peleshko M. In [3] the results of experimental research are presented and three methods of reinforcing timber beams with tape reinforcement are presented, which made it possible to almost double their carrying capacity.

The analysis of the presented research confirms the possibility of performing numerical research in PC LIRA-CAD by analogy with the engineering method of calculating laminated timber elements with composite reinforcement [4], as a relevant and innovative method of research.

It should be noted that the modeling of reinforcement elements, namely composite tapes made of Sika CarboDur S 1012 carbon fibers in the LIRA-CAD program complex requires a separate study and a more detailed study for a more accurate approval of the research results on the reinforcement of various types of structures with them.

Definition of unsolved aspects of the problem

Research conducted at this stage is purely theoretical. They show the theoretical experience of strengthening laminated timber beams with composite tapes.

This article presents numerical research in PC LIRA-CAD and compares the calculation results of beams of different lengths reinforced with composite tapes and without reinforcement at all under the action of different uniformly distributed loads.

Problem statement

The world experience of implementing structures made of laminated timber proves the feasibility of using such structures. LTCs are especially widespread for covering medium, long, and very long spans (over 100 m). This is due to the fact that laminated timber effectively combines all the best qualities of timber as a construction material, such as relatively high strength and leveling of defects that are present in solid wood. One of the methods of increasing the bearing capacity of LTC is their reinforcement in various ways, including composite tapes.

The purpose of this work is to study the stress-strain state of laminated timber beams reinforced with composite tapes in comparison with laminated timber beams without reinforcement by modeling them in PC LIRA-CAD using volumetric and flat finite elements and to approbate the results through the comparison of the researched elements of different lengths under the action of different uniformly distributed loads.

The other purpose is to investigate the results of modeling Sika CarboDur S 1012 carbon fiber composite tapes with flat finite elements in the LIRA-SAPR software complex.

Main material and results

The beams of rectangular cross-section glued from boards of the same strength class with reinforcement with composite tapes (Fig. 1 (b)) and without it (Fig. 1 (a)) on two hinged supports, loaded with a uniformly distributed load of intensity: 2 kN/m, 4 kN/m, 6 kN/m, 8 kN/m, and spans: 4 m, 6 m, and 8 m were chosen as the object of numerical researches.

The cross-section of the beams consists of eight layers of timber boards of the same strength class C35, which were modeled by three-dimensional FE No. 36 for numerical research. The overall dimensions of the cross-section of the beams are H = 24 cm, b = 10 cm, with the following mechanical properties: modulus of elasticity of timber along the fibers E1 = E0, mean = 13000 MPa, modulus of elasticity of timber across the fibers E2 = E3 = E90, mean = 430 MPa, shear modulus G = Gmean = 810 MPa. When modeling beams reinforced with Sika CarboDur S 1012 composite tapes, which were modeled with flat FE No. 44, their mechanical characteristics were additionally specified: modulus of elasticity along the fibers E1 = E0, mean = 170,000 MPa.

The isopolies of vertical deformations and normal stresses along the timber fibers according to the results of numerical tests of FEM for beams made of laminated timber with and without composite tape reinforcement spans: 6 m., with a uniformly distributed load of 2 kN/m is presented in Fig. 2 - 3.

Full results of FEM numerical research for laminated timber beams with and without composite tape reinforcement for 4 m, 6 m, 8 m spans were investigated and all variants of uniformly distributed load 2 kN/m, 4 kN/m, 6 kN/m, 8 kN/m, presented in table 1-4.

From the conducted numerical research, it is clear that for beams made of laminated timber of the same strength class reinforced with composite tapes under a uniformly distributed load of 2.0 kN/m, the tensile load-bearing capacity increases by more than 25% compared to similar beams without reinforcement with composite tapes. And the movement of such beams when reinforced with tapes is reduced by more than 15%. For reinforced beams under a uniformly distributed load of 4.0 kN/m, the tensile load-bearing capacity increases by more than 25% compared to similar beams without composite tape reinforcement. And the movement of such beams when reinforced with tapes is reduced by almost 20%. For reinforced beams with a uniformly distributed load of 6.0 kN/m, the tensile load-bearing capacity increases from 26 to 29%, compared to similar beams without composite tape reinforcement. And the movement of such beams when reinforced with tapes decreases by 17-19%. For reinforced beams under a uniformly distributed load of 8.0 kN/m, the tensile load-bearing capacity also increases from 26 to 29%, compared to similar beams without composite tape reinforcement. And the movement of such beams when reinforced with tapes decreases by 17-19%.

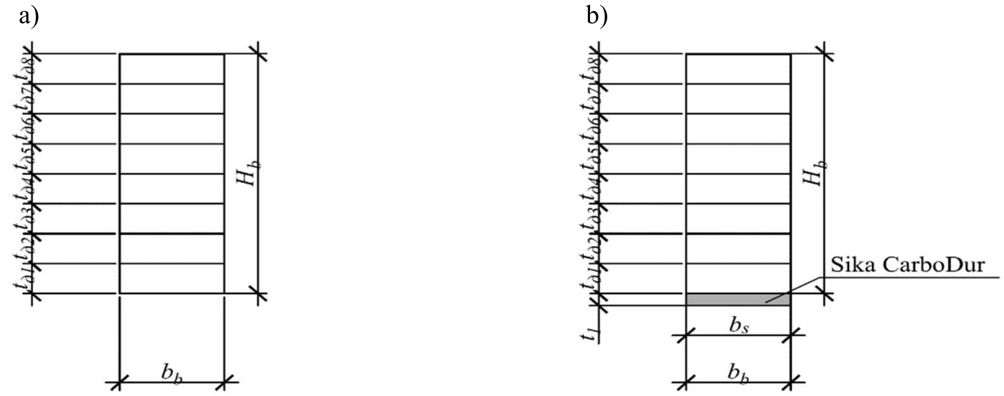

Figure 1 – Geometric diagram of the cross-section of the beam without reinforcement (a) and reinforced with composite tape (b).

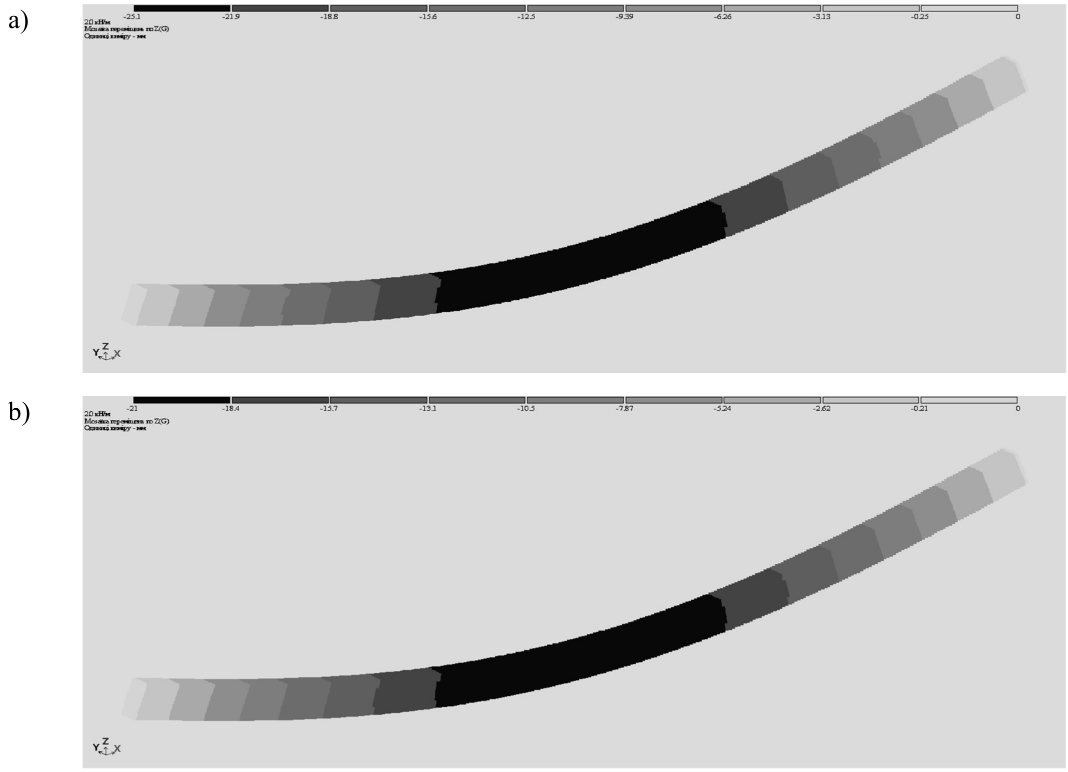

Figure 2 – Isopolies of vertical deformations in glued laminated timber beams without reinforcement (a) and reinforced beams (b) with a span of 6 m at an evenly distributed load of 2 kN/m

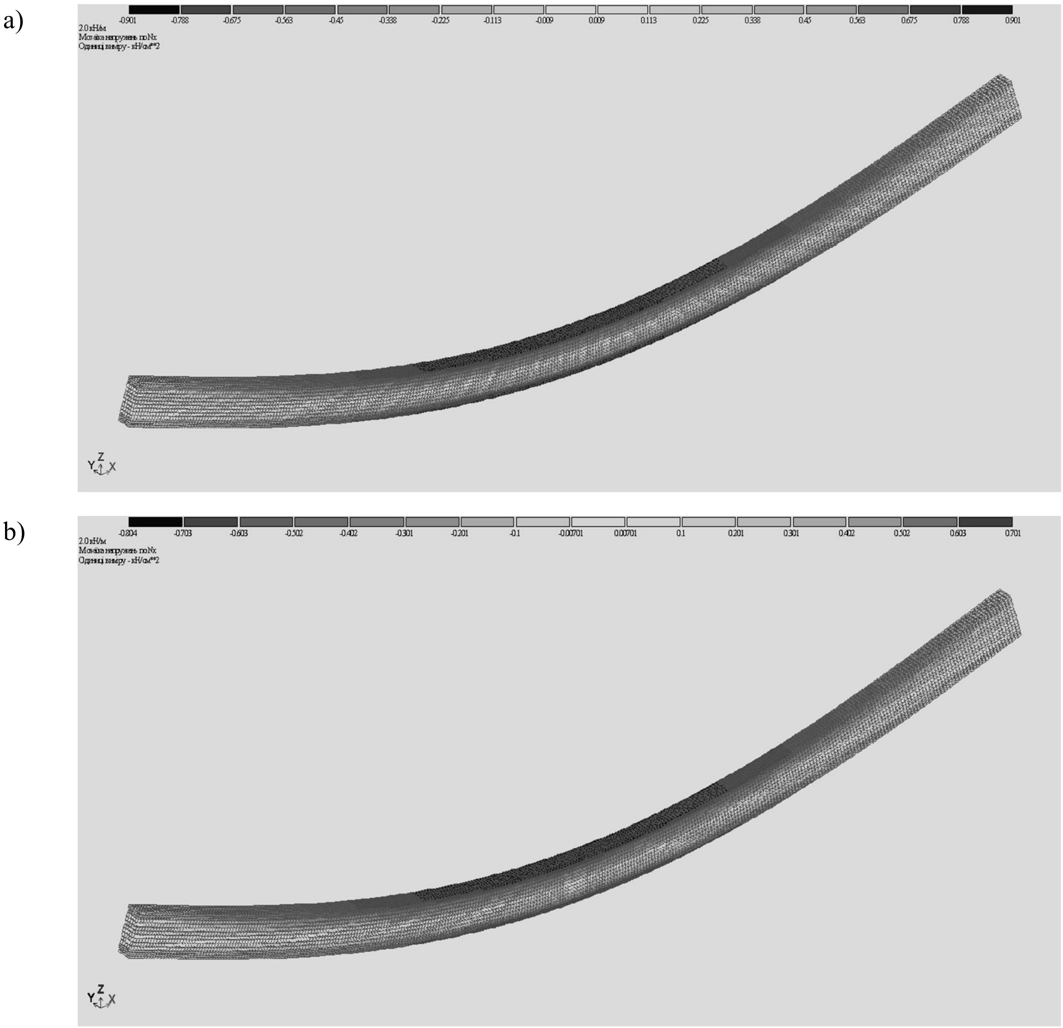

Figure 3 – Isopolies of normal stresses in beams from glued laminated timber without reinforcement (a) and reinforced beams (b) with a span of 6 m at evenly distributed load of 2 kN/m

Table 1 – Values of deflections and maximum normal stresses for glued laminated timber beams of the same strength class with and without reinforcement at a uniformly distributed load of 2.0 kN/m

Span, m		4		6		8	
Methods of calculation	*EI* (*W_x*), kNsm^2 (sm^3)	*w*, mm	$\sigma_{m,d}$, kN/cm^2	*w*, mm	$\sigma_{m,d}$, kN/cm^2	*w*, vv	$\sigma_{m,d}$, kN/cm^2
FEM with volumetric FE No. 36	without reinforcement	4,76	0,402	25,1	0,901	72,3	1,60
FEM with volumetric FE No. 36 and flat FE No. 44	reinforced with composite tape	4,06	0,318	21	0,701	61,2	1,27
Percentage difference		17%	26%	20%	29%	18%	26%

Table 2 – Values of deflections and maximum normal stresses for glued laminated timber beams of the same strength class with and without reinforcement at a uniformly distributed load of 4.0 kN/m

Span, m		4		6		8	
Methods of calculation	EI (W_x), kNsm^2 (sm^3)	w, mm	$\sigma_{m,d}$, kN/cm^2	w, mm	$\sigma_{m,d}$, kN/cm^2	w, mm	$\sigma_{m,d}$, kN/cm^2
FEM with volumetric FE No. 36	without reinforcement	9,51	0,804	50,1	1,8	145,0	3,2
FEM with volumetric FE No. 36 and flat FE No. 44	reinforced with composite tape	8,11	0,635	42,0	1,4	122,0	2,54
Percentage difference		17%	27%	19%	29%	19%	26%

Table 3 – Values of deflections and maximum normal stresses for glued laminated timber beams of the same strength class with and without reinforcement at a uniformly distributed load of 6.0 kN/m

Span, m		4		6		8	
Methods of calculation	EI (W_x), kNsm^2 (sm^3)	w, mm	$\sigma_{m,d}$, kN/cm^2	w, mm	$\sigma_{m,d}$, kN/cm^2	w, mm	$\sigma_{m,d}$, kN/cm^2
FEM with volumetric FE No. 36	without reinforcement	14,3	1,21	75,2	2,7	217,0	4,8
FEM with volumetric FE No. 36 and flat FE No. 44	reinforced with composite tape	12,2	0,953	63,0	2,1	184,0	3,8
Percentage difference		17%	27%	19%	29%	18%	26%

Table 4 – Values of deflections and maximum normal stresses for glued laminated timber beams of the same strength class with and without reinforcement at a uniformly distributed load of 8.0 kN/m

Span, m		4		6		8	
Methods of calculation	EI (W_x), kNsm^2 (sm^3)	w, mm	$\sigma_{m,d}$, kN/cm^2	w, mm	$\sigma_{m,d}$, kN/cm^2	w, mm	$\sigma_{m,d}$, kN/cm^2
FEM with volumetric FE No. 36	without reinforcement	19	1,61	100,0	3,6	289,0	6,4
FEM with volumetric FE No. 36 and flat FE No. 44	reinforced with composite tape	16,2	1,27	84	2,8	245,0	5,07
Percentage difference		17%	27%	19%	29%	18%	26%

For a more illustrative example, comparative graphs of the ratio of displacements to uniformly distributed loads in the researched beams with corresponding spans of 4 m, 6 m, and 8 m were created (Fig. 4-6) and comparative graphs of the ratio of the maximum normal stresses of the researched beams to uniformly distributed loads applied to them (Fig. 7-9.)

If we compare the results of these tables (Tab. 1-4) and graphs (Fig. 4-9), we can conclude that with increased loads the percentage of amplification remains practically unchanged. From the obtained results, it becomes clear that the reinforcement of the stretched zone of the beam made of laminated timber allows to significantly reduce its deformability and normal tensile stresses along the fibers.

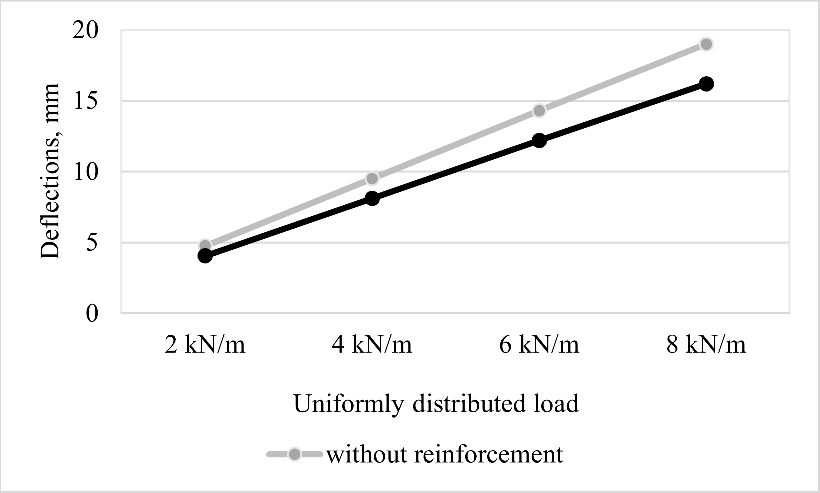

Figure 4 – Graph of the ratio of displacements to evenly distributed loads in the researched beams with a span of 4 m

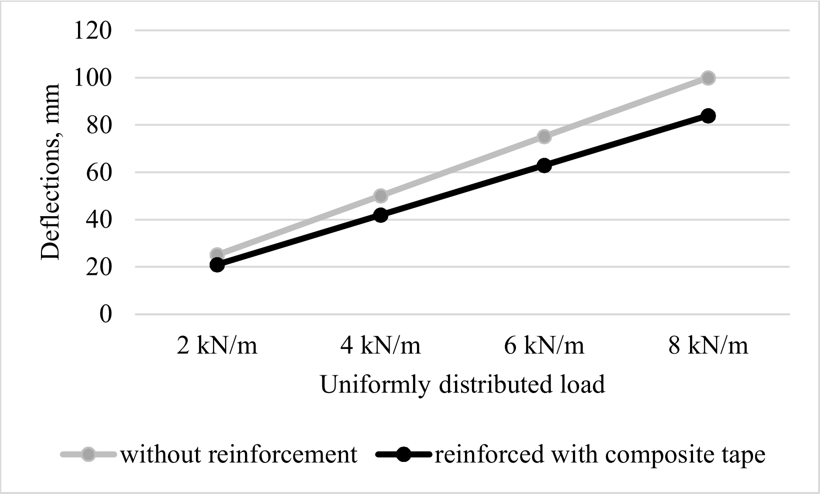

Figure 5 – Graph of the ratio of displacements to evenly distributed loads in the researched beams with a span of 6 m

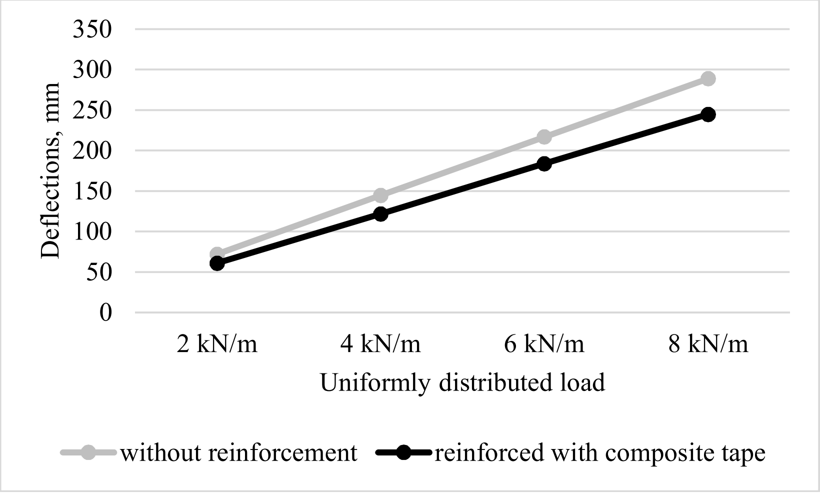

Figure 6 – Graph of the ratio of displacements to evenly distributed loads in the researched beams with a span of 8 m

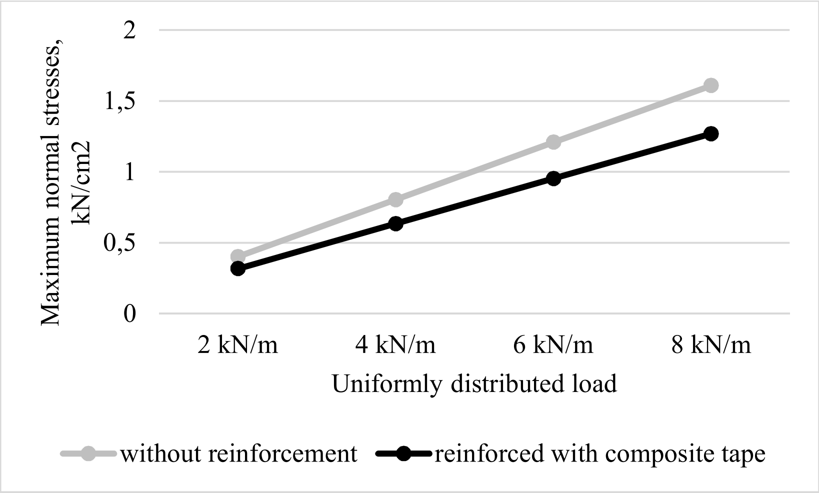

Figure 7 – Graph of the ratio of maximum normal stresses to evenly distributed loads in the researched beams with a span of 4 m

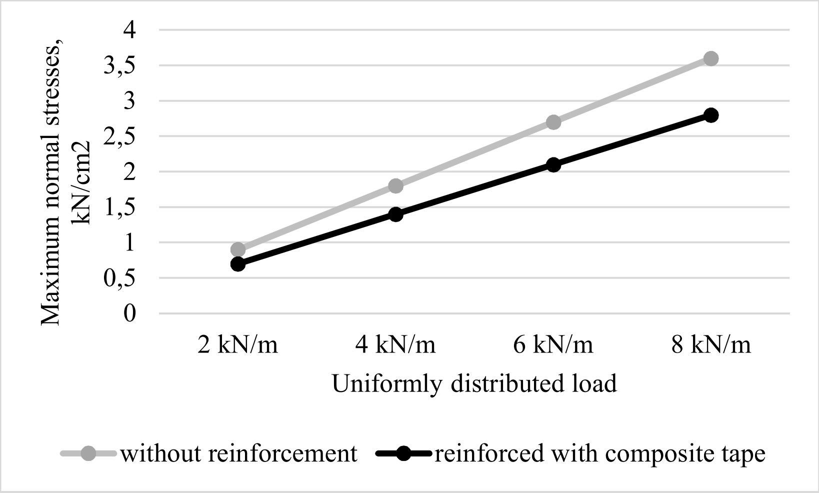

Figure 8 – Graph of the ratio of maximum normal stresses to evenly distributed loads in the researched beams with a span of 6 m

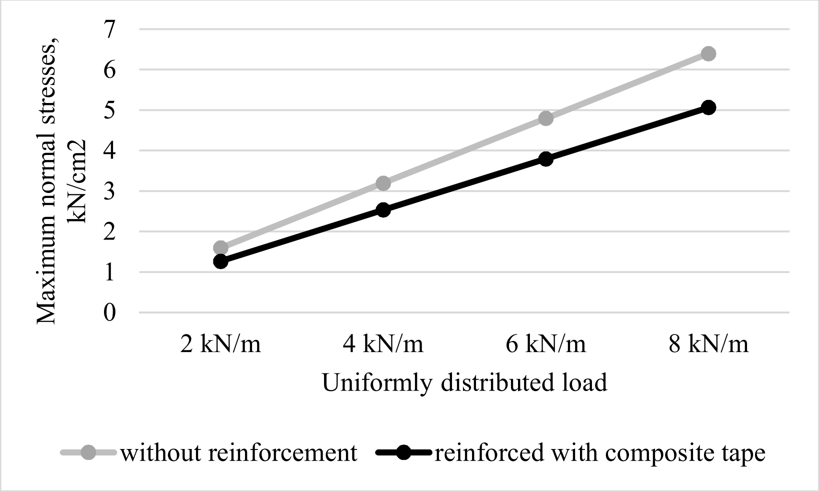

Figure 9 – Graph of the ratio of maximum normal stresses to evenly distributed loads in the researched beams with a span of 8 m

Conclusions

As can be seen from the results obtained according to the finite element calculation in PC LIRA-CAD, beams made of glued boards of strength class C35, which were modeled by three-dimensional finite elements FE No. 36, reinforced with a composite tape made of carbon fibers Sika CarboDur S 1012, which were modeled by flat finite elements FE No. 44 have on average 18% lower vertical strains and 27% lower normal stresses than similar laminated timber beams not reinforced with composite strips. We can note that with an increase in load, the percentage difference between the values of deflections and maximum normal stresses of such beams practically does not change. Therefore, this method of reinforcement can be considered effective.

And in connection with the absence of calculation instructions or any other engineering approach to structures made of laminated timber reinforced with composite tapes in domestic regulatory documents [5 - 7] the perspective of these researches is relevant. Reinforcement with composite tapes of other structures made of laminated timber, such as frames, arches, trusses, and panels made of cross-laminated timber, requires a separate study.

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