Research Article

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Properties of wood-based composites manufactured from densified beech wood in viscoelastic and plastic region of the force-deflection diagram (FDD)

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Abstract: It is still little or no knowledge about the properties of layered wood-based composites and nonwood components in the viscoelastic and plastic region of the force-deflection diagram (FDD). The properties of composites in this area are influenced by several factors such as the composition of the layered composite, the method of modification of the individual layers, the type of adhesive used, etc. This paper focuses on the analysis of the effect of the thickness of individual layers (5 and 9 mm) of beech wood (*Fagus sylvatica* L.), modification of these layers with different degrees of densification (10, 20, 30, and 40%) and the type of the nonwood component (carbon and high-strength glass fibers) used to reinforce the layered composite on the properties of materials in the plastic region of the FDD. The paper describes the impact of selected factors and those interactions behavior of the tangent modulus in the whole FDD. This is the first study that describes the development of layered wood-based composites and nonwood components in the viscoelastic and plastic region and analyzes the impact of most imported types of modifications on the characteristics in the viscoelastic and plastic regions.

Keywords: layered composite material, tangent modulus, chord modulus, wood bending, bending

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1 Introduction

Wood is one of the most preferred building materials by architects and engineers due to its high specific strength, renewability, carbon locking ability, and ease of processing with minimal energy. Besides, wood properties can also be engineered to meet specific requirements by various technological inventions such as densification, modification (chemical and thermal), and composites. The creation of a wood-based composite with specific properties for a given purpose is currently one of the most progressive research areas. As the name suggests, wood composite refers to a material composed of two or more components with wood as the primary component. A binder connects the individual components. In order to develop a composite with improved material properties, it is essential to know the properties of each component [1]. With the information on the properties of each component and the ways to improve the properties, it is possible to control the properties of the composite for any given end application [2]. As wood is a biological material with anisotropic properties (different properties in orthogonal directions), it is necessary to minimize the anisotropy and improve its properties so that the composite can have desired properties for any given end application. Based on the general categorization of composites, these layered composites have different properties; the material type, orientation, and reinforcement are essential parameters in controlling the final properties of the composite [3–5]. A wide range of uses characterize the layered composites. Wood in its natural form is characterized by structural deviations (defects), increasing its heterogeneity and reducing its load-bearing capacity when used as beams [6,7]. By cutting the beam into thin layers (lamellae) and then gluing them together with a random arrangement of defects, a beam with higher strength can be achieved, but not necessarily with increased stiffness. By arranging the lamellae so that lamellae with a higher number of defects are in the central part of the beam, their mechanical properties can be increased. A way to improve the properties of the laminated beam even more significantly is the elimination of all defects or the densification of individual lamellae and subsequent layering of the bonded lamellae. The most significant improvement can be achieved by combining laminated wood with an element with increased strength and stiffness [8–10]. Properties of wood-based composites are less heterogeneous as compared to solid. Therefore, strength distribution in glued laminated wood is narrower and higher than its distribution in solid wood [11]. The surface layers in layered wood composites play an important role as these layers experience the maximum stresses when the materials are loaded. There are currently several ways of strengthening or improving the quality of surface layers. The most common improvement method used in parallel layered wood composites is the densification of wood layers or its reinforcement with nonwood components based on high-strength carbon and glass fibers. A common disadvantage of these composite structures is delamination, which manifests itself in multiple cracks in the case of these materials. Local instability and crack growth in glued laminated timber can cause the overall instability of large structural elements, leading to failure of the entire structure in extreme cases [12–16]. The type and quality of the adhesive also play an essential role in the direction in which the strength properties of the layered material will move under stress. Selecting the type and form of adhesive depends on the nature of the adherents, the end-use requirements, and the gluing processes [17]. Many different adhesives are used for wood composites [18].

Knowledge of the properties of homogeneous and composite materials in the plastic region is of considerable practical importance [8]. Availability of relevant information on the material properties and the factors that affect them can help in modeling new composite structures with desirable properties [19]. Recently, there has been greater emphasis on using optimized materials [20]. The properties of the optimized materials can be modified in various ways in the composite by using the appropriate adhesive, appropriate alignment, and placement of individual layers, suitable nonbiological components, or nanomaterials [21]. If such conditions are met, then a layer of a suitably selected wood with specific properties for the given purpose of use can also be considered as an optimized material.

On the contrary, a wrong way of applying an expensive and sophisticated composite material results in its poor performance [22,23]. The load and corresponding deflections within the elastic region and breaking load are taken into account to calculate the modulus of elasticity (MOE) and the strength of wood, respectively. However, the shape of the FDD in the plastic region is crucial to ascertain the material's behavior beyond the recoverable deformation. The purpose of this study was to improve the material property of layered composites through densification of wood lamellae as well as reinforcement with stiffer material (carbon and glass fibers) and assess the properties of the layered composites in the plastic zone. The material properties in the plastic zone were ascertained by calculating the tangent moduli. The tangent modulus at any stress refers to the slope of the tangent concerning the horizontal axis. The tangent modulus within the limit of proportionality (elastic region) is constant and equivalent to Young's modulus of elasticity, while the values of the tangent modulus beyond the elastic region are different and decrease until the sample fails [24,16].

As tangent modulus can be calculated at any specified stress or strain, and its value keeps changing in the plastic zone, it can serve as an ideal tool to compare the properties and behavior of different laminates in the plastic zone. Identifying stresses in the plastic area of the stress–strain diagram is not very widespread. This paper focused on identifying this characteristic concerning the experimental factors such as change of density after densification of beech wood and reinforcing components in the composition of laminated wood-based materials and its influence on tangent moduli.

2 Materials and methods

2.1 Materials

The experiment was carried out using radial beech wood (*Fagus sylvatica* L.) lamellae from Poľana, east of Zvolen, Slovakia. The lamellae were produced in two thicknesses of 5 and 9 mm, and the constant width of the lamellae was 35 mm. The length of the individual lamellae was determined so that it was possible to test the test specimens 20 times the span of the lower supports of the test device (140, 220, 240, and 400 mm). Another material in the tested layered material was a reinforcing component in the form of high-strength fiber fabrics. Two types of fabrics were used: the first one was based on high-strength SikaWrap 150C/30 carbon fibers (SIKA CZ), and the second was based on type E glass fibers (KITTFORT). All components in the composite were glued together using single-component PVAc adhesive (AG-COLL 8761/L D3). The adhesive was applied unilaterally manually with a spread range of 150–180 $g \cdot m^{-2}$.

2.2 Methods

2.2.1 Lamellae densification

The individual input lamellae were densified by a standard thermomechanical method in double-sided heated press TOS Rakovník at a temperature of 140°C (±5°C). The densification was performed in four stages (10, 20, 30, and 40%) for the original thickness of the lamellae. An overview of the basic pressing parameters is listed in Table 1. The densification resulted in a change in the moisture content and density; these parameters were determined according to the relevant standards ISO 13061-1 [25] and ISO 13061-2 [26].

2.2.2 Creation of test sets

After modifying the lamellae, layered materials were produced using other components listed in the Materials section. The tested sets can be classified as a single layer (default), two layer without a nonwood component, a two layer with a nonwood component, and a three layer with a nonwood component. A total of 60 test sets were created. Each test set consisted of 30 test specimens. A basic diagram of test sets with the identification of individual materials in the composite can be seen in Figure 1.

Representative photographs of the individual test group can be seen in Figure 2(a–f).

Table 1: Technical parameters of the pressing process

Degree of densification	Pressure (MPa)	Time (min)
5 mm lamellae (10%)	30.2	5
9 mm lamellae (10%)	37.7	9
5 mm lamellae (20%)	31.5	6
9 mm lamellae (20%)	39.3	10
5 mm lamellae (30%)	34.2	7
9 mm lamellae (30%)	42.7	11
5 mm lamellae (40%)	36.3	8
9 mm lamellae (40%)	43.4	12

2.2.3 Mechanical testing

The monitored mechanical characteristics were obtained by three-point bending with a methodology corresponding to standard EN 310 [27]. The principle of the three-point bending consists of loading an element with an insulated force in the middle of its length, according to the diagram in Figure 3. Testing was performed on the universal testing machine FPZ 100. Important parameters of the testing itself include the loading speed (3 mm · min^{-1}) so that the testing itself is 30–90 s long and the variable span of the lower support pins so that it corresponds to 20 times the thickness for all tested specimens.

3 Evaluation and calculation

3.1 Processing the FDD

Our measurements showed that a second-degree parabola could describe the nonlinear part of the FDD with the index of determination close to 0.999. The different

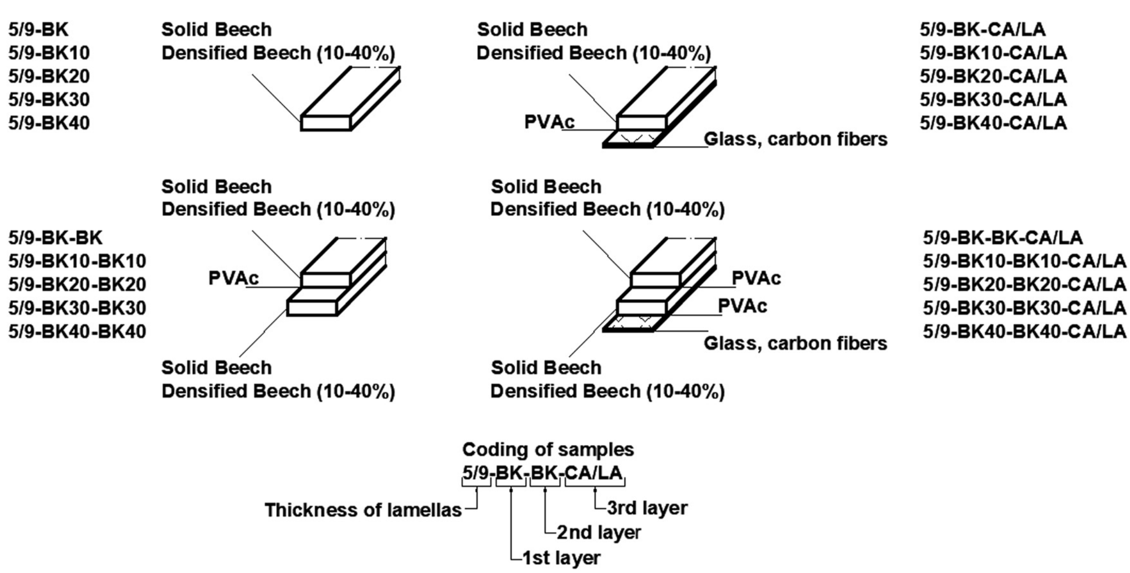

Figure 1: Types of test sets.

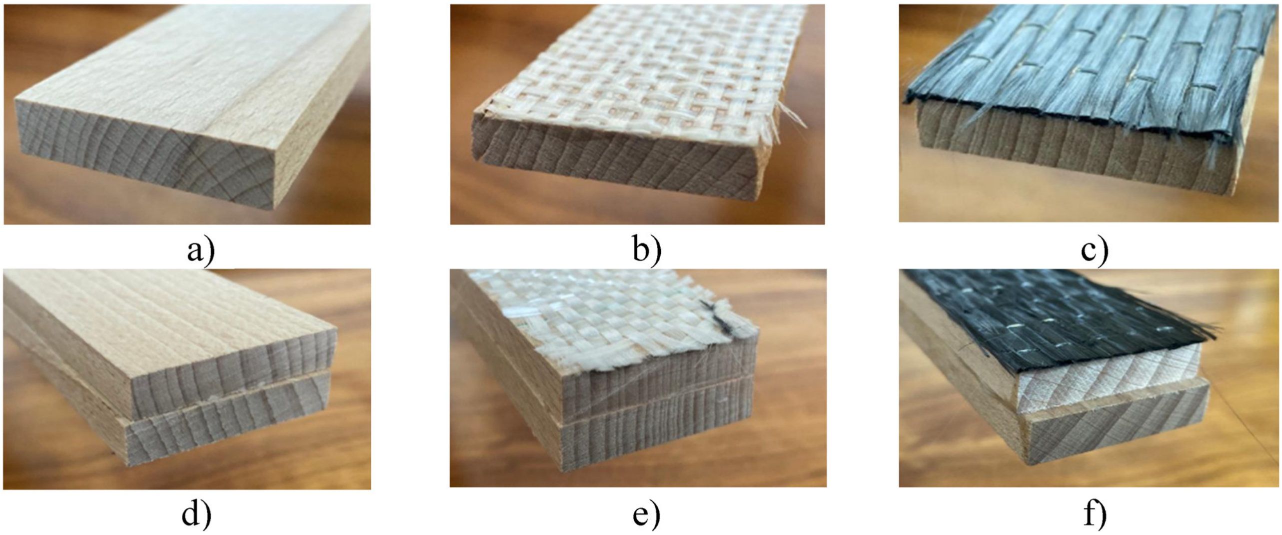

Figure 2: Representative photographs of individual test group: (a) single layer, (b) two-layered with glass fibers, (c) two-layered with carbon fibers, (d) two-layered without NWC, (e) three-layered with glass fibers, and (f) three-layered with carbon fibers.

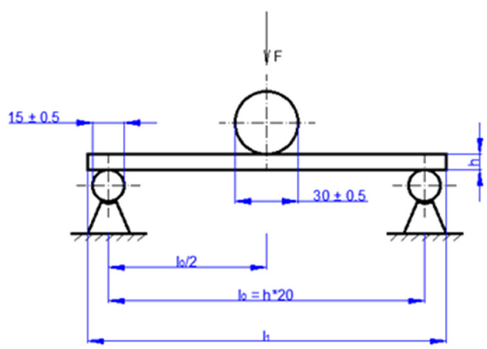

Figure 3: Diagram of three-point bending test according to EN 310 1993.

stages of the FDD evaluation are shown in Figure 4. The last part of this figure (Figure 4d) shows the two derivations: one is the numerical derivation based on the data and the second is obtained from the derivation of the parabolic equation. The agreement of these two can be considered the proof of the correct approach.

3.2 Tangent and chord modulus

The tangent modulus is the first derivative of either the FDD or the force-displacement diagram. In the elastic region, it is a constant modulus of elasticity or the following value, which was published in refs. [19,28]:

$$\frac{F_E}{y_E} = \frac{E_A \cdot 48 \cdot I}{l_0^3}. \quad (1)$$

A description of the nonelastic region of the FDD can be used in the equation for second-degree parabola (2).

$$F = a \cdot y^2 + b \cdot y + c. \quad (2)$$

The tangent modulus of the force-displacement diagram becomes

$$\frac{\partial F}{\partial y} = 2 \cdot a \cdot y + b. \quad (3)$$

For the tangent moduli and chord modulus for 3-point bending, the following equations apply:

$$E_E = \frac{F_E}{y_E} \cdot \frac{l_0^3}{48I}, \quad (4)$$

$$E_{MV} = \frac{F_{MV}}{y_{MV}} \cdot \frac{l_0^3}{48I}, \quad (5)$$

$$E_P = \frac{F_P}{y_P} \cdot \frac{l_0^3}{48I}, \quad (6)$$

$$CH_M = \frac{F_P - F_E}{y_P - y_E} \cdot \frac{l_0^3}{4bh^3}, \quad (7)$$

where F_P is the force at the elastic limit (N), F_E is the force at the proportionality limit (N), y_P is the deflection at the modulus of rupture (mm), y_E is the proportionality limit (mm), y_{MV} is the deflection expressed as the average value between y_E and y_P (mm), l_0 is the span of the support during bending (mm), and b (width) and h (thickness) are the cross-sectional dimensions of the test specimen (mm).

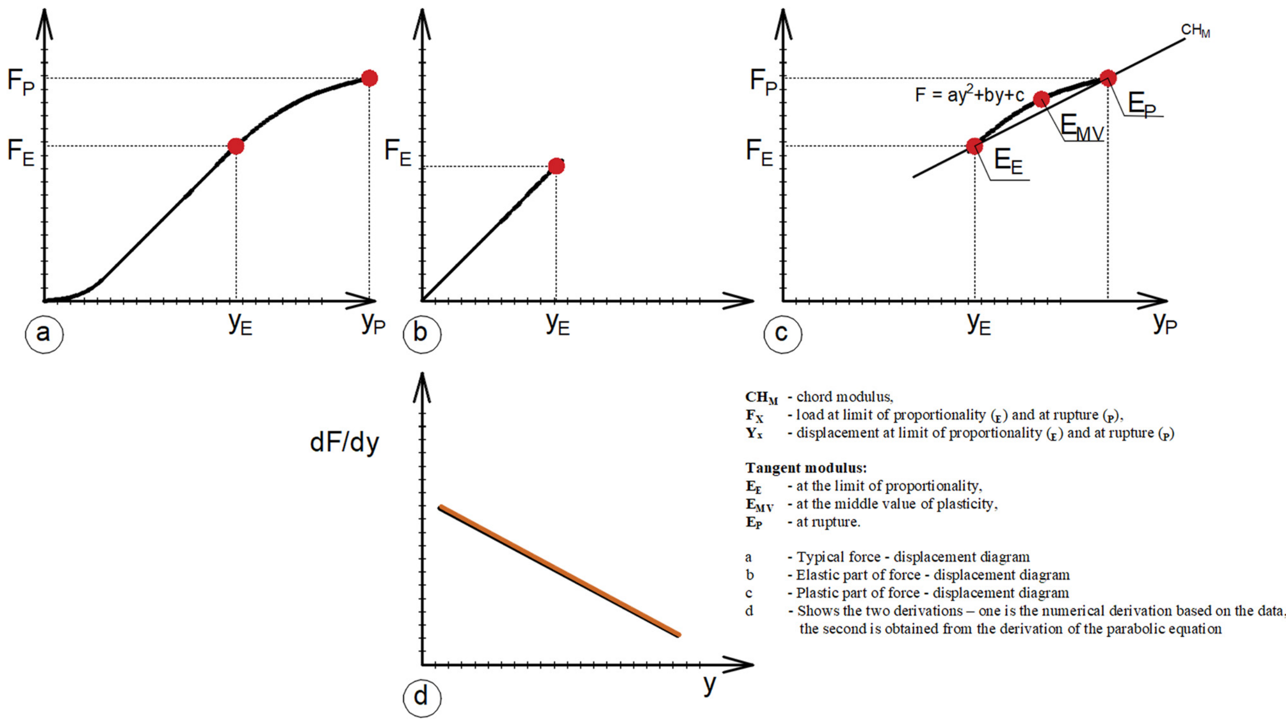

Figure 4: Different stages of the FDD evaluation.

The standard for testing moduli of elasticity requires the fulfillment of the condition $l_0 = 20h$. Then, we can introduce the constant K:

$$K = \frac{l_0^3}{4bh^3}. \tag{8}$$

If the condition mentioned above is not strictly fulfilled, it can be a source of substantial errors.

3.3 Statistical analysis

A four-factor analysis of variance of the effect of individual factors on the characteristics was used to evaluate the results. Based on the P-level value, it was determined whether a factor affected the values of monitored characteristics. Diagrams were constructed for the 95% confidence interval, the results were verified with Duncan's tests, and Spearman's rank-order correlation was carried out.

4 Results and discussion

In Figure 5a and b, the density profile for each type of test sample is shown. The changes in the density caused by the densification process are evident. However, it is also possible to observe inefficient densification at higher degrees of densification (30–40%), given by the chosen densification method. It is possible to observe slightly different trends of changes in the tangent modulus at 5 and 9 mm densified lamellae. The changes in density profiles explaining the different changes in the tangent modulus of the different types of lamellae can be seen in Figure 5a and b.

Several research teams addressed the influence of density profiles and the density of densified wood. Densification aims to increase the density of the material and achieve an optimal density distribution along with the height of the material. This distribution largely depends on the chosen densification method and has a significant effect on the overall mechanical properties of the compacted wood [16,23,29].

Table 2 shows the average values of the chord modulus (CH_M) and tangent moduli at the point of elasticity (E_E), at the middle point (E_{MV}), and at the point of modulus of rupture (E_P), as well as the corresponding coefficient of variations for all test groups. The changes in the density caused by densification are also evident in the table. In terms of the percentage change of the Chord modulus, we can see that the highest percentage change is recorded in modification by densification, and there was a higher increase in values in 5 mm lamellae. From layering and densification, we can see that the most significant increase in values is recorded in layered composites with lamellae densified by 20%; the trends were observed

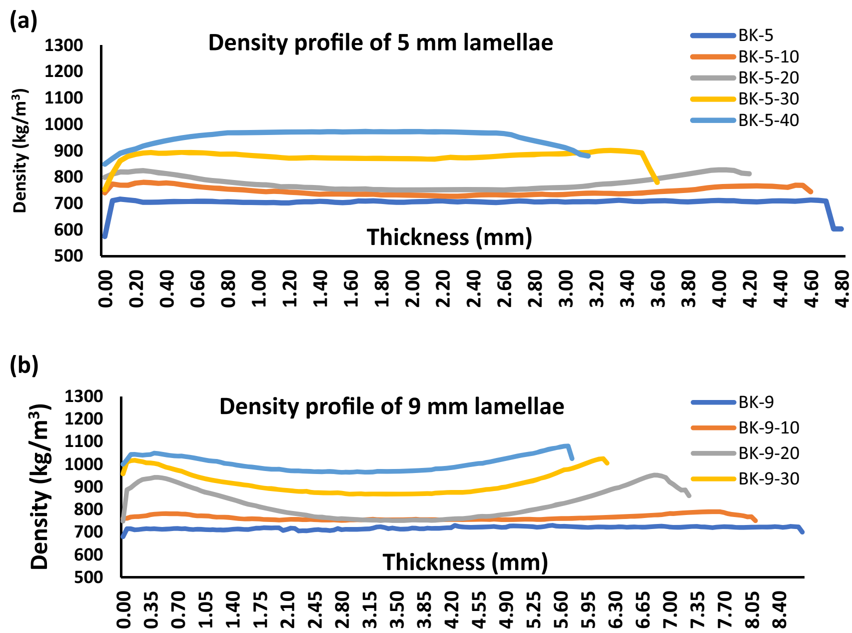

Figure 5: (a) Density profile of each type of test sets made from (a) 5 mm lamellae and (b) 9 mm lamellae.

when high-strength fibers are not transparent. Regarding percentage changes of E_E in single- and two-layer unreinforced materials, there is a similar trend in the CH_M. An interesting trend of changes in values for the thickness of the lamellae can be seen in reinforced two-layer materials; more significant changes can be seen in the application of carbon fibers in 5 mm materials, with an opposite trend in 9 mm materials. Looking at the three-layer materials, this trend is ambiguous with densification; above 20%, changes are reversed in the opposite direction. When the most significant positive changes were caused by densification of individual layers, in terms of layering using densified lamellae, in the application of lamellae densified by 30 and 40%, a decline in the change was recorded again. Looking at the changes in the tangent modulus at the modulus of rupture “E_P,” it is possible to see a significant change in the monitored values caused by the densification of individual lamellae, as in previous cases, the input thickness of the lamellae. From the perspective of layering itself, we can observe an increase in values up to the application of lamellae densified by 20%, with a subsequent decrease in glued materials composed of lamellae with 30 and 40% densification. According to the coefficient of correlations calculated between the density of the lamellae and monitored plasticity characteristics, it is clear that the correlation is primarily medium. Correlations calculated between densification degree of the lamellae and monitored plasticity characteristics are primarily small, and between nonwood components of the lamellae and monitored characteristics of plasticity are primarily small or trivial.

4.1 Effect of densification on tangent moduli

Figure 6a and b show the effect of densification of 5 mm beech lamellae on the values of the monitored characteristics describing the plastic properties of the material. Figure 6a shows the average values of the monitored, measured characteristics, and Figure 6b shows the percentage change in the values of the monitored characteristics for the untreated reference lamellae. The data provided in Figure 6a show a positive effect of the densification of individual layers, which was manifested by an increase in all monitored characteristics (CH_M, E_E, E_{MV}, and E_P). The data in Figure 6b show that densification achieved the highest increase in the tangent moduli at the modulus of rupture E_P. In this case, 10% densification resulted in an increase of up to 95% in EP values. If we compare the monitored values of input materials with other wood-based composite materials, e.g., with OSB boards mentioned in Sikora et al. [28], we can see significantly lower tangent modulus values in OSB boards; however, the data in the article confirm the development trend of the tangent modulus values.

Figure 6b shows that as the degree of densification increases, the percentage increase in all monitored characteristics decreases; this is probably due to the increasing

Table 2: Mean values of CH_M, E_E, E_{MV}, and E_P for the individual sets of test specimens and the coefficient of variation for beech wood

	Code	CH_M (MPa)	r, r_{II}, r_{III}	E_E (MPa)	r, r_{II}, r_{III}	E_{MV} (MPa)	r, r_{II}, r_{III}	E_P (MPa)	r, r_{II}, r_{III}	Density ($kg \cdot m^{-3}$)	No.
Single layer	5-BK	6,314 (14.9)	***, ***	10,761 (10.6)	***, ***	6,193 (15.6)	***, ***	5,116 (2.5)	***, ***	687.90 (5.3)	30
	5-BK10	10,461 (12.7)		15,651 (10.0)		10,340 (12.9)		9,960 (3.1)		789.59 (3.7)	30
	5-BK20	10,209 (10.1)		14,871 (8.9)		10,103 (10.1)		9,747 (5.3)		828.98 (3.7)	30
	5-BK30	9,659 (13.4)		14,000 (15.2)		9,544 (13.6)		8,262 (9.8)		914.20 (7.1)	30
	5-BK40	10,198 (11.4)		15,891 (11.2)		10,042 (11.4)		9,263 (6.6)		995.95 (5.8)	30
	9-BK	6,747 (18.8)		10,286 (14.6)		6,656 (18.8)		5,356 (10.1)		699.50 (6.7)	30
	9-BK10	8,294 (16.3)		11,325 (17.9)		8,125 (20.5)		7,801 (3.7)		730.84 (4.1)	30
	9-BK20	9,038 (11.0)		12,595 (9.6)		8,986 (11.2)		7,824 (7.2)		817.99 (3.7)	30
	9-BK30	8,529 (17.9)		12,068 (15.2)		8,395 (18.7)		7,340 (12.2)		902.29 (4.5)	30
	9-BK40	9,124 (17.0)		13,301 (15.5)		8,962 (19.5)		7,129 (5.7)		1007.63 (4.2)	30
Two-layer without NWC	5-BK-BK	6,823 (22.5)	**, *	11,067 (11.7)	***, **	6,731 (22.8)	**, *	5,171 (7.5)	*, *	698.77 (5.4)	30
	5-BK10-BK10	8,394 (8.2)		13,154 (9.1)		8,274 (8.4)		7,152 (7.5)		783.35 (2.6)	30
	5-BK20-BK20	9,152 (18.3)		13,675 (9.9)		8,990 (19.0)		7,181 (7.1)		842.05 (4.1)	30
	5-BK30-BK30	7,451 (15.7)		12,390 (10.8)		7,347 (16.5)		6,066 (4.6)		890.74 (5.2)	30
	5-BK40-BK40	6,960 (18.5)		11,719 (17.2)		6,723 (20.9)		5,382 (10.9)		912.65 (11.8)	30
	9-BK-BK	6,909 (12.3)		10,260 (16.1)		6,808 (12.2)		6,202 (7.0)		705.57 (3.6)	30
	9-BK10-BK10	7,594 (18.6)		10,123 (14.7)		7,477 (19.7)		6,535 (5.4)		741.68 (3.3)	30
	9-BK20-BK20	8,632 (13.2)		11,538 (14.4)		8,473 (13.2)		7,082 (5.9)		836.01 (4.0)	30
	9-BK30-BK30	7,548 (16.4)		11,075 (10.6)		7,417 (17.4)		6,482 (5.3)		870.08 (4.2)	30
	9-BK40-BK40	7,829 (18.1)		11,969 (10.8)		7,697 (18.6)		6,282 (13.1)		978.55 (3.7)	30
Two-layer with NWC	5-BK-CA	5,517 (17.6)	**, **, **	11,434 (18.2)	***, ***, ***	5,283 (18.2)	*, *, *	4,471 (18.4)	**, **, **	712.33 (4.7)	30
	5-BK-LA	5,527 (18.7)		10,424 (11.7)		5,338 (19.4)		4,372 (11.5)		757.52 (5.2)	30
	5-BK10-CA	6,815 (18.3)		11,349 (13.7)		6,673 (19.0)		5,110 (8.5)		763.99 (5.5)	30
	5-BK10-LA	6,051 (11.3)		11,096 (12.5)		5,905 (12.1)		4,399 (9.7)		786.06 (3.3)	30
	5-BK20-CA	7,403 (17.8)		12,402 (14.9)		7,278 (18.1)		6,373 (7.7)		863.56 (5.4)	30
	5-BK20-LA	6,235 (16.8)		11,471 (14.1)		6,034 (18.3)		5,626 (7.4)		833.06 (5.2)	30
	5-BK30-CA	6,071 (10.3)		15,986 (11.6)		5,517 (13.2)		4,596 (19.3)		901.36 (7.8)	30
	5-BK30-LA	6,712 (16.3)		12,208 (14.8)		6,498 (16.9)		5,153 (9.8)		989.08 (4.0)	30
	5-BK40-CA	6,934 (14.2)		17,671 (11.3)		6,401 (17.4)		5,586 (9.7)		1107.10 (4.9)	30
	5-BK40-LA	6,383 (18.9)		12,006 (19.1)		6,208 (20.0)		5,589 (9.2)		1102.85 (4.4)	30
	9-BK-CA	5,900 (19.3)		10,545 (17.8)		5,806 (19.3)		4,218 (18.4)		705.31 (5.0)	30
	9-BK-LA	6,060 (19.5)		10,693 (19.6)		5,909 (20.0)		4,713 (9.1)		745.78 (4.2)	30
	9-BK10-CA	6,988 (17.6)		11,176 (14.3)		6,939 (17.2)		5,516 (8.4)		734.97 (5.5)	30
	9-BK10-LA	6,762 (14.3)		11,839 (15.0)		6,599 (14.3)		5,717 (8.8)		800.38 (4.9)	30
	9-BK20-CA	6,950 (12.3)		11,616 (15.9)		6,832 (12.3)		5,878 (10.0)		816.33 (5.3)	30
	9-BK20-LA	7,333 (16.5)		13,461 (11.9)		7,071 (17.6)		5,847 (5.9)		884.08 (3.4)	30
	9-BK30-CA	6,772 (14.2)		14,675 (12.2)		6,366 (16.1)		4,917 (8.2)		931.14 (4.6)	30
	9-BK30-LA	5,138 (16.7)		8,771 (14.7)		4,987 (17.9)		3,122 (15.3)		935.67 (4.1)	30

(*Continued*)

Table 2: *Continued*

	Code	CH_M (MPa)	r, r_{II}, r_{III}	E_E (MPa)	r, r_{II}, r_{III}	E_{MV} (MPa)	r, r_{II}, r_{III}	E_P (MPa)	r, r_{II}, r_{III}	Density ($kg \cdot m^{-3}$)	No.
	9-BK40-CA	6,714 (12.2)		14,812 (11.8)		6,244 (14.0)		5,088 (7.4)		1032.16 (2.4)	30
	9-BK40-LA	6,001 (21.2)		9,918 (16.8)		5,827 (23.3)		4,407 (7.5)		1060.78 (3.1)	30
Three layer	5-BK-BK-CA	6,294 (21.1)	***, **, *	10,510 (13.0)	****, ***, **	6,198 (21.5)	***, **, *	5,016 (7.5)	***, ***, **	701.95 (5.3)	30
	5-BK-BK-LA	5,746 (19.2)		9,717 (14.9)		5,654 (19.6)		4,010 (10.7)		705.44 (5.8)	30
	9-BK-BK-CA	7,001 (26.6)		10,976 (18.2)		6,921 (27.9)		5,393 (6.5)		688.55 (5.6)	30
	9-BK-BK-LA	7,101 (18.4)		11,914 (10.9)		6,980 (18.9)		5,371 (21.1)		716.69 (5.9)	30
	5-BK10-BK10-CA	8,274 (20.2)		12,592 (16.2)		81,72 (21.2)		7,279 (4.9)		762.53 (5.9)	30
	5-BK10-BK10-LA	7,351 (12.5)		13,263 (9.7)		7,202 (13.0)		7,178 (5.8)		777.30 (4.4)	30
	9-BK10-BK10-CA	6,625 (11.3)		15,342 (9.8)		6,246 (13.2)		5,118 (8.1)		724.13 (6.1)	30
	9-BK10-BK10-LA	6,886 (17.1)		12,203 (20.8)		6,721 (18.0)		5,110 (7.8)		784.28 (4.0)	30
	5-BK20-BK20-CA	8,734 (17.9)		18,552 (12.8)		8,259 (18.9)		7,202 (5.7)		848.82 (5.2)	30
	5-BK20-BK20-LA	6,178 (18.9)		11,358 (22.3)		6,047 (18.9)		5,313 (6.5)		829.66 (9.7)	30
	9-BK20-BK20-CA	5,821 (17.7)		10,171 (14.7)		5,704 (17.4)		4,091 (10.0)		812.26 (5.0)	30
	9-BK20-BK20-LA	5,900 (18.2)		9,411 (20.9)		5,800 (18.3)		4,020 (8.1)		865.88 (3.1)	30
	5-BK30-BK30-CA	5,475 (16.8)		11,233 (14.7)		5,298 (17.7)		4,522 (6.4)		899.00 (4.8)	30
	5-BK30-BK30-LA	7,047 (15.2)		10,898 (10.8)		6,921 (15.7)		5,209 (6.7)		962.47 (3.8)	30
	9-BK30-BK30-CA	6,626 (18.6)		10,785 (22.1)		6,496 (18.1)		5,531 (9.6)		890.04 (2.5)	30
	9-BK30-BK30-LA	7,438 (14.5)		13,144 (12.2)		7,237 (14.7)		6,618 (3.8)		905.16 (3.2)	30
	5-BK40-BK40-CA	7,482 (12.1)		13,583 (9.6)		7,246 (13.3)		6,496 (4.6)		1100.39 (5.0)	30
	5-BK40-BK40-LA	7,006 (12.4)		11,431 (9.3)		6,823 (12.1)		5,499 (5.6)		1058.44 (3.6)	30
	9-BK40-BK40-CA	7,061 (14.5)		12,572 (16.3)		6,794 (15.6)		5,492 (4.7)		906.92 (2.4)	30
	9-BK40-BK40-LA	5,946 (17.7)		9,355 (13.5)		5,773 (19.3)		4,801 (23.5)		931.60 (3.2)	30

Values in parentheses are coefficients of variation (CV) in %, CH_M, chord modulus, E_E, tangent modulus at the point of elasticity, E_{MV}, tangent modulus at the middle point, E_P, tangent modulus at the MOR point, r, the correlation between monitored characteristics and the density of lamellae, r_{II}, the correlation between monitored characteristics and the degree of densification, r_{III}, the correlation between monitored characteristics and nonwood components of the lamellae.
Interpretation of the correlation coefficient:.
*: 0.0–0.1, trivial correlation.
**: 0.1–0.3, small correlation.
***: 0.3–0.5, mean correlation.
****: 0.5–0.7, great correlation.
*****: 0.7–0.9, very large correlation.
******: 0.9–1.0, lmost perfect correlation.

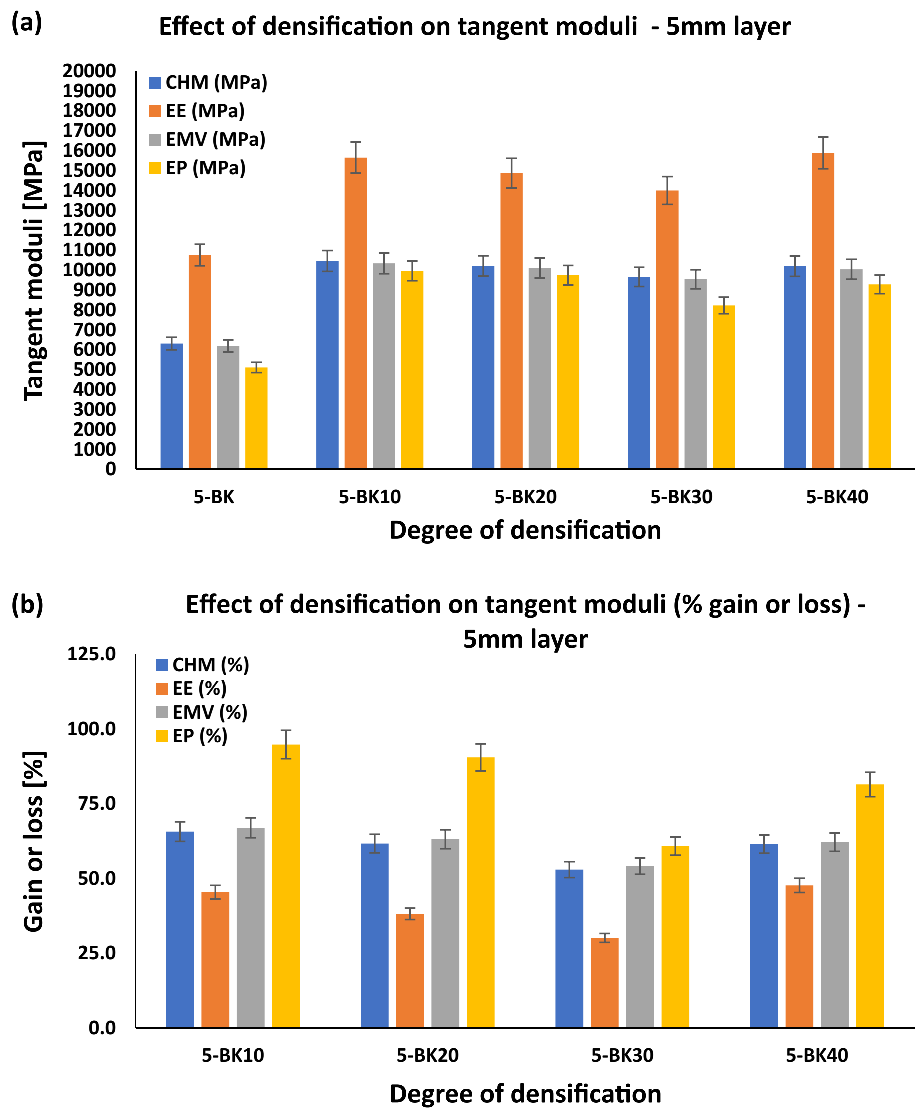

Figure 6: (a) Effect of densification of 5 mm thick beech layer on tangent moduli and (b) effect of densification of 5 mm thick beech layer on tangent moduli expressed in percentage gain or loss concerning nondensified wood.

destruction of the material's internal structure. The material deforms after exceeding the 10% deflection limit, but in the material's internal structure, there is an increase in micro-defects, which results in a decrease in the values of the percentage change. At 40% densification, we see a change in the course and a slight but tendentious increase in the percentage change from the values measured at 30% densification and a slight increase for E_E by 20% densification. It would therefore be interesting to determine the effect of higher degrees of densification. We compared our results with the results published in Gaff and Babiak [19], where the effect of 10 and 20% densification was addressed. The waveforms of the values of tangent moduli are very similar to the values measured by us at 10 and 20% densification. The results we found significantly expand knowledge in the use of densified wood in layered materials.

In 9 mm lamellae (Figure 7a and b), the trend is more evident. As the degree of densification increases, so do the values of the monitored characteristics. A slight stagnation in the percentage change achieved by densification can be observed at 30% densification, where we see a nonsignificant slight decrease in the values of the monitored characteristics; however, at 40% densification, they began to increase again.

The difference in the behavior between 5 mm and 9 mm laminated wood is mainly caused by the limit thickness, affecting the development of tangential stresses. In terms of absolute values, significantly higher values of the monitored characteristics are achieved by layering thinner materials [4,5,7,10].

The inefficiency of higher degrees of densification (30 and 40%) can be explained mainly by SEM analysis (Figure 8). In this figure, one can see the morphology of wood densified by 30%. In addition to increasing the density itself (Figure 5a and b), there was also the formation of cracks within the individual cellular elements of wood. This fact causes a decrease in measured tangent moduli. These cracks were not observed for wood lamellae densified by 10 and 20%. These findings can explain the decrease in values at higher degrees of densification, reflected in other types of materials stated in this study.

4.2 Effect of reinforcement on tangent moduli

Figure 9a and b show the effect of reinforcement on the values of the monitored tangent moduli (Figure 9a) and the effect of reinforcement on percentage changes in the values of tangent moduli (Figure 9b). We compared the results of single-layer (5 and 9 BK) test specimens with the results published in Gaff and Babiak [19], and the comparison of the results shows an agreement.

If we compare our results (Figure 9a) with the results of Sikora et al. (2018) measured on different particle boards, we can observe that the values of the tangent modulus measured on the grown wood reach 100%

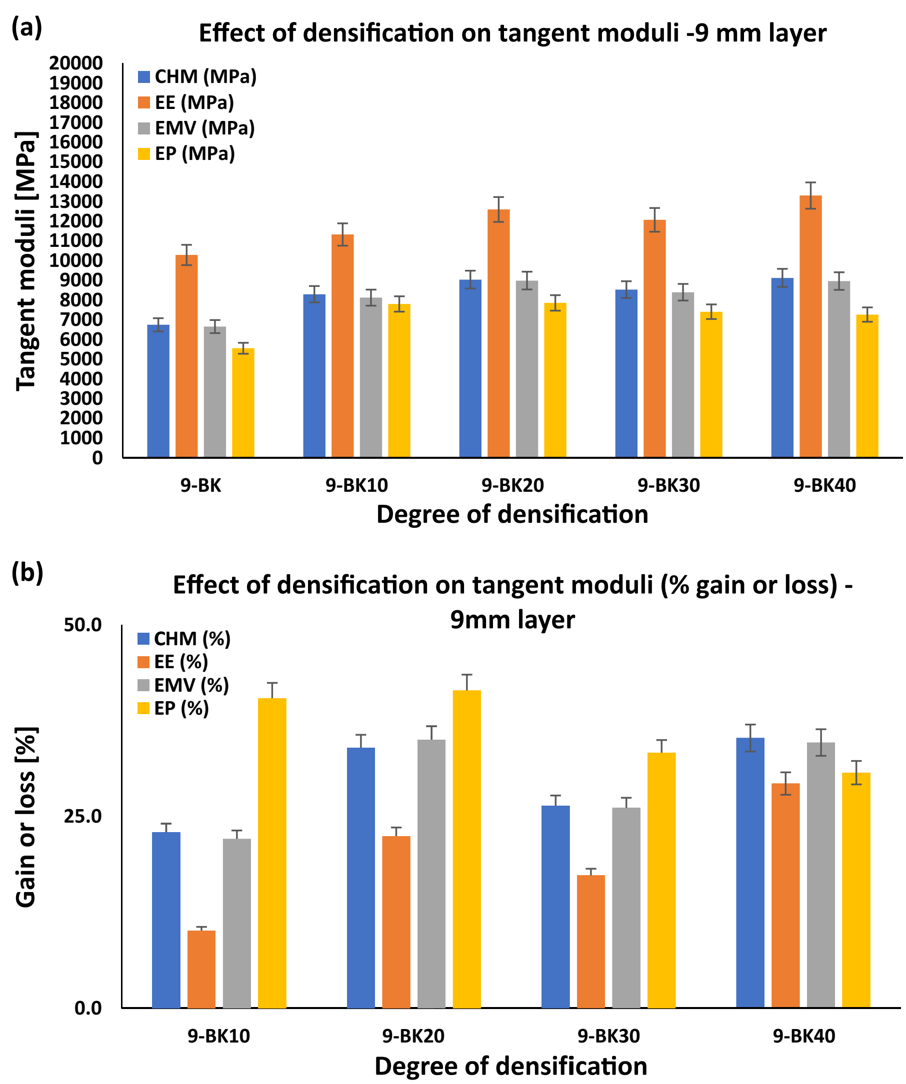

Figure 7: (a) Effect of densification of 9 mm thick beech layer on tangent moduli and (b) effect of densification of 9 mm thick beech layer on tangent moduli expressed in percentage gain or loss concerning nondensified wood.

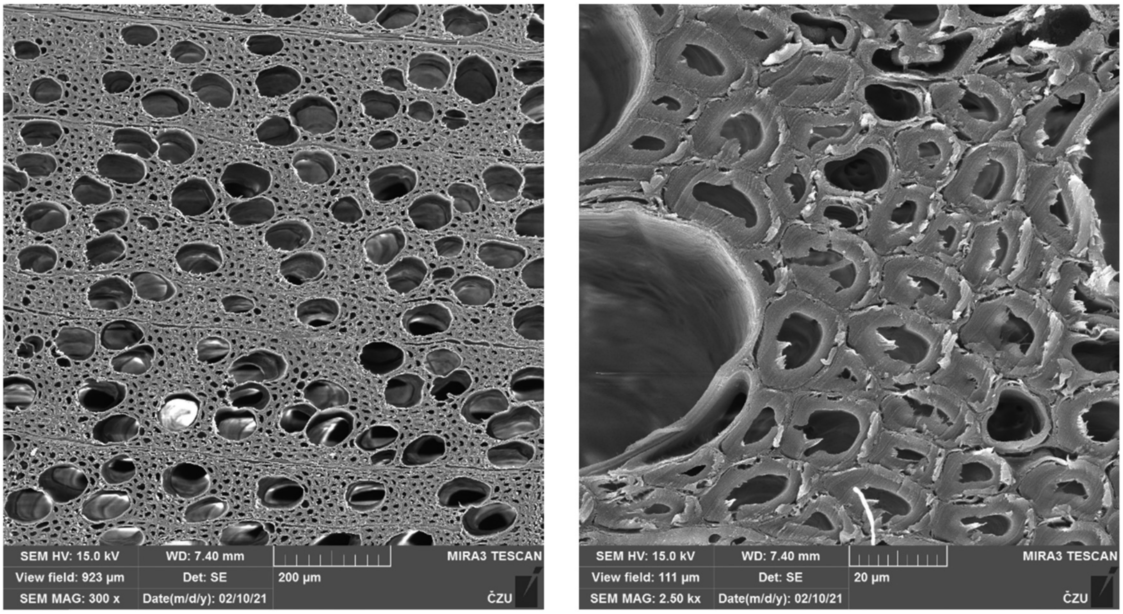

Figure 8: SEM analysis of densified wood, densified by 30%.

higher values than on the mentioned composite materials. All those results correlated with the results published by Mohanty et al. [30], Faruk et al. [31], Mohamad et al. [32], Kobbe [33], and Almeida et al. [34]. The figures clearly show that at both thicknesses of wood, the effect of reinforcement caused the decrease of the values of the monitored characteristics. A slight increase (in the range of 2.5–6.2%) can be observed with the tangent modulus at the limit of proportionality "E_E," but this cannot be considered statistically significant based on the values of the significance level *P*. We assume that this increase was achieved due to the nonwood component and the wood's adhesion and cohesion with the nonwood component (Figure 9b). After crossing the limit of proportionality, the destruction of the material increases, which results in a decrease in values of the observed characteristics in the plastic area.

4.3 The combined effect of densification and reinforcement on tangent moduli

The interaction between densification and reinforcement on the tangent modulus is shown in Figure 10a, and the percentage change caused by the interaction of these parameters is shown in Figure 10b.

The figures show that the interaction of both monitored parameters, densification, and reinforcement, does not bring the expected results to the values of characteristics describing the material's properties beyond the limit of proportionality (Figure 10a and b). In all observed cases and for all monitored characteristics, we can see a decrease in values of the monitored characteristics compared to specimens without reinforcement. We can observe that with an increase in the degree of densification in material composition, the tangent moduli decrease for the reference material.

Figure 11a and b show the interaction between reinforcement and the degree of densification in 9 mm lamellae on the values of the monitored characteristics in the plastic region (Figure 11a) and the percentage changes (Figure 11b).

In terms of the percentage change of the Chord modulus (Figure 11b), we can see that the highest percentage change is recorded in modification by densification and there was a higher increase in values in 5 mm lamellae. From the perspective of layering and densification, we can see that the most significant increase in values is recorded in layered composites with lamellae densified by 20% (Table 2). The results show the trend of changes in the E_E. In single- and two-layer unreinforced materials, there is a similar trend as in the CH_M. An interesting trend of changes in values for the thickness of the lamellae can be seen in reinforced two-layer materials; more significant changes can be seen in the application of carbon fibers in 5 mm materials, with an

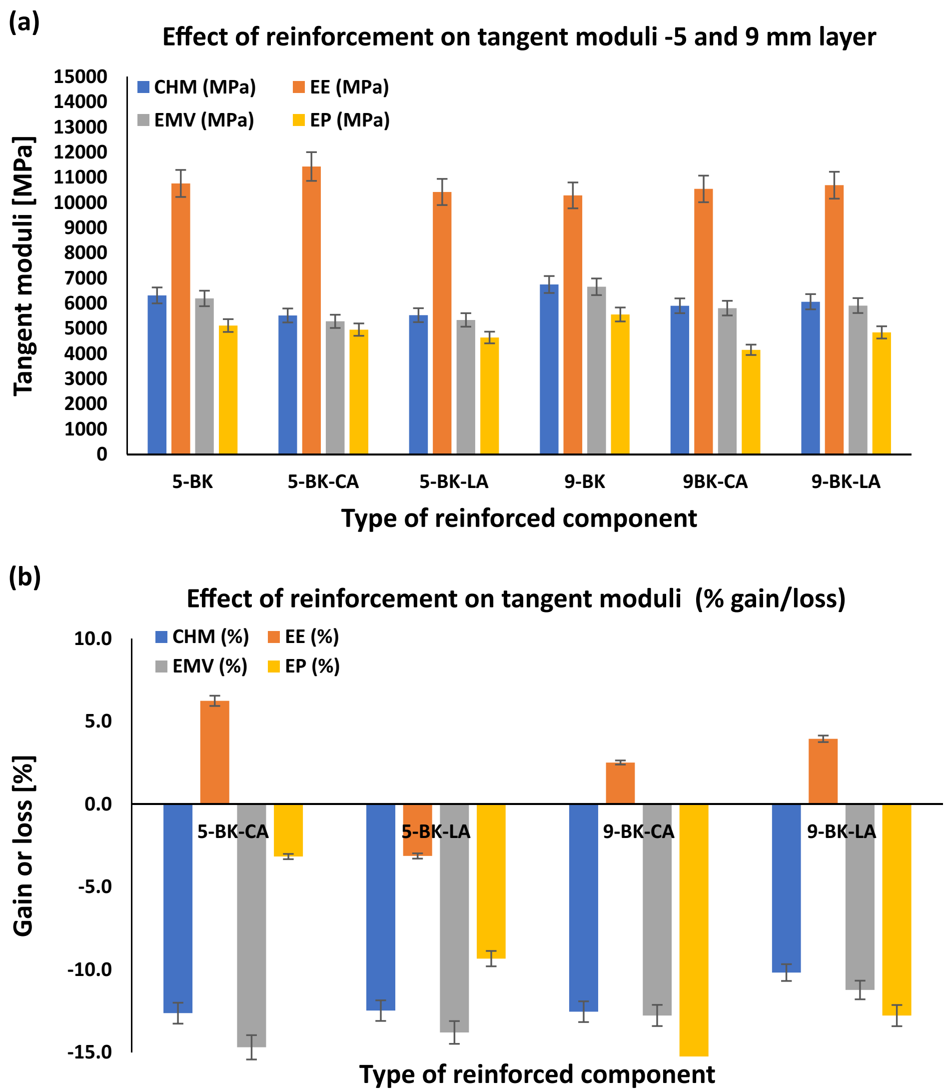

Figure 9: (a) Effect of reinforcement of wood with reinforcement fibers on tangent moduli. (b) Effect of reinforcement on tangent moduli expressed in percentage gain or loss concerning nonreinforced samples.

opposite trend in 9 mm materials. Looking at the three-layer materials, this trend is ambiguous with densification; above 20%, changes are reversed in the opposite direction. The percentage changes in the tangent modulus E_{MV} shown in Figure 11b primarily copy the trend of changes in the case of the chord modulus. The most significant changes were caused by densification of individual layers in layering using densified lamellae; in applying lamellae densified by 30 and 40%, a decline in the change was recorded again. Observing the changes in the tangent modulus values at the modulus of rupture "E_P" (Figure 11a and b), it is possible to see a significant change in the monitored values caused by the densification of individual lamellae; as in previous cases, this change was affected by the input thickness of the lamellae. From the perspective of layering itself, we can observe an increase in values up to the application of lamellae densified by 20%, with a subsequent decrease in glued materials composed of lamellae with 30 and 40% densification.

4.4 Spearman's rank-order correlation

Tables 3–6 show the results of Spearman's rank-order correlation analysis. The results of the correlation analysis of nonlayered materials (Table 3) show a high

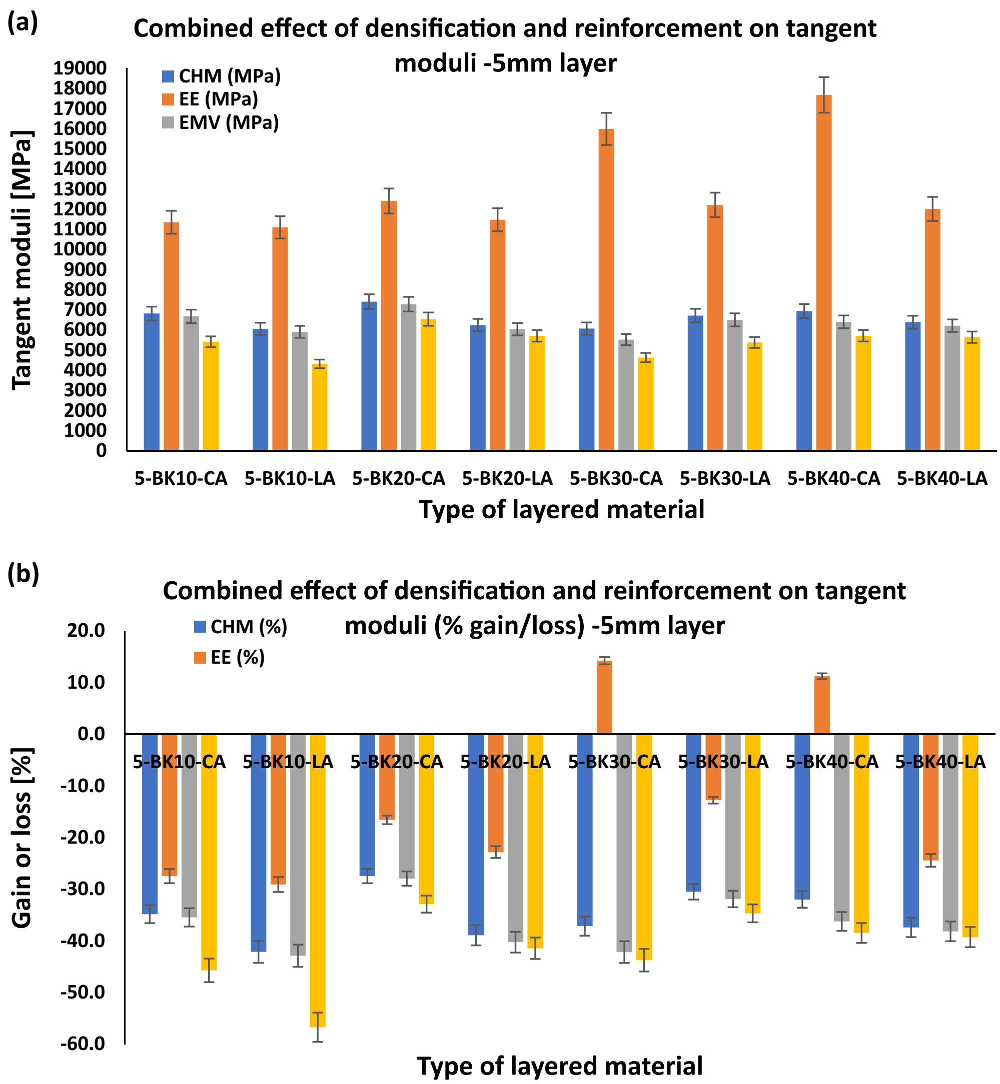

Figure 10: The combined effect of densification and reinforcement (a) on tangent moduli in 5 mm thick beech lamellae and (b) expressed in percentage gain or loss on tangent moduli in 5 mm thick lamellae.

dependence of all monitored characteristics, both concerning the input thickness and the degree of densification.

Table 4 shows the correlation analysis of the two-layer material without applying high-strength fibers for the input thickness of lamellae and the densification of individual layers. For these materials, a high dependence for the input thickness of the lamellae was only demonstrated for the characteristics E_E and E_P. In the case of densification of individual layers, the dependence of both layers was only proven for the characteristics E_E and E_P. The dependence between all individual characteristics was also demonstrated.

Table 5 shows the results of the correlation analysis for two-layer materials reinforced with high-strength fibers where, as in the previous analysis, dependence on the thickness of materials is only shown for the characteristics E_E and E_P. For material densification, significant dependence on the characteristics CH_M, E_E, and E_P was demonstrated. In terms of high-strength fibers, dependence was proven for all monitored characteristics.

Table 6 shows the results of the correlation analysis for the three-layer materials tested. It is clear from these results that there is a high dependence between the thickness and densification of all layers on all the characteristics

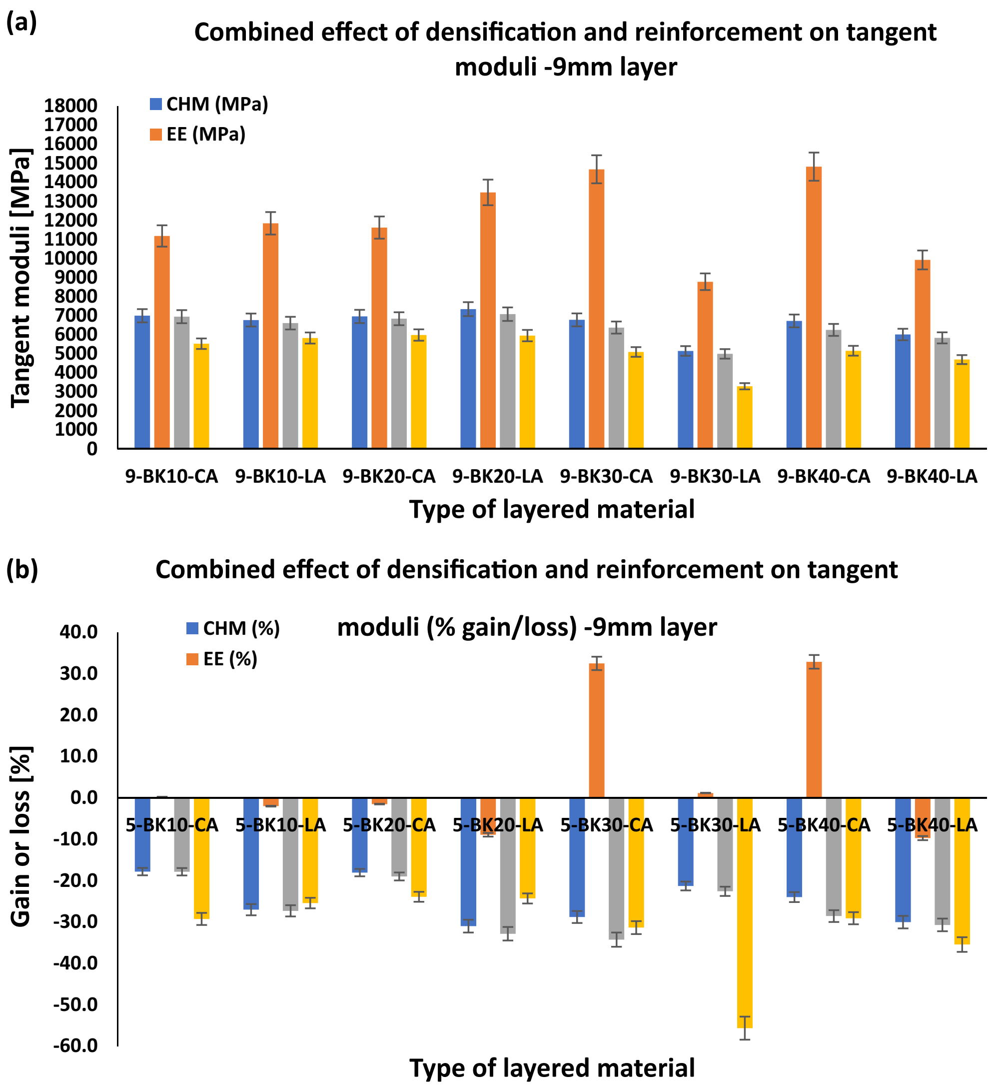

Figure 11: The combined effect of densification and reinforcement on (a) tangent moduli in 9 mm thick beech lamellae and (b) expressed in percentage gain or loss on tangent moduli in 9 mm thick lamellae.

Table 3: Spearman's rank correlation coefficient of bending characteristics for one-layer materials

Variables	Thickness (mm)	Densification	CH_M (MPa)	E_{MV} (MPa)	E_E (MPa)	E_P (MPa)
Thickness (mm)	1.000	—	—	—	—	—
Densification	—	1.000	—	—	—	—
CH_M (MPa)	−0.314	0.442	1.000	—	—	—
E_{MV} (MPa)	−0.307	0.433	0.996	1.000	—	—
E_E (MPa)	−0.484	0.462	0.783	0.769	1.000	—
E_P (MPa)	−0.333	0.444	0.832	0.828	0.835	1.000

CH_M, E_{MV}, E_E, E_P. In terms of the reinforcing material, dependence is only shown between the characteristics E_E and E_P. As with other materials, the interdependence between all characteristics was demonstrated.

Table 4: Spearman's rank correlation coefficient of bending characteristics for two-layer materials without nonwood components

Variables	Thickness (mm)	Densificati of 1st layer	Densificati of 2nd layer	CH_M (MPa)	E_{MV} (MPa)	E_E (MPa)	E_P (MPa)
Thickness (mm)	1.000	—	—	—	—	—	—
Densification of 1st layer	0.000	1.000	—	—	—	—	—
Densification of 2nd layer	0.000	1.000	1.000	—	—	—	—
CH_M (MPa)	−0.021	0.041	0.041	1.000	—	—	—
E_{MV} (MPa)	−0.019	0.030	0.030	0.995	1.000	—	—
E_E (MPa)	−0.391	0.191	0.191	0.604	0.582	1.000	—
E_P (MPa)	−0.150	0.193	0.193	0.843	0.826	0.682	1.000

Table 5: Spearman's rank correlation coefficient of bending characteristics for two-layer materials with nonwood components

Variables	Thickness (mm)	Densificati of 1st layer	Reinforcement	CH_M (MPa)	E_{MV} (MPa)	E_E (MPa)	E_P (MPa)
Thickness (mm)	1.000	—	—	—	—	—	—
Densification of 1st layer	−0.002	1.000	—	—	—	—	—
Reinforcement	−0.002	−0.002	1.000	—	—	—	—
CH_M (MPa)	0.037	0.132	−0.172	1.000	—	—	—
E_{MV} (MPa)	0.055	0.057	−0.126	0.981	1.000	—	—
E_E (MPa)	−0.124	0.344	−0.344	0.550	0.424	1.000	—
E_P (MPa)	0.094	0.183	−0.187	0.866	0.822	0.608	1.000

Table 6: Spearman's rank correlation coefficient of bending characteristics for three-layer materials with nonwood components

Variables	Thickness (mm)	Densificati of 1st layer	Densificati of 2nd layer	Reinforcement	CH_M (MPa)	E_{MV} (MPa)	E_E (MPa)	E_P (MPa)
Thickness (mm)	1.000	—	—	—	—	—	—	—
Densification of 1st layer	−0.002	1.000	—	—	—	—	—	—
Densification of 2nd layer	−0.002	1.000	1.000	—	—	—	—	—
Reinforcement	−0.002	−0.002	−0.002	1.000	—	—	—	—
CH_M (MPa)	−0.135	0.258	0.258	−0.066	1.000	—	—	—
E_{MV} (MPa)	−0.136	0.220	0.220	−0.043	0.993	1.000	—	—
E_E (MPa)	−0.221	0.398	0.398	−0.211	0.641	0.591	1.000	—
E_P (MPa)	−0.095	0.309	0.309	−0.181	0.894	0.868	0.696	1.000

5 Conclusions

(1) Densification of lamellae increases tangent moduli values. Among the densification level, lamellae densified by 10% of their thickness showed the best results. With increasing degrees of densification, especially with densification by 30 and 40%, there was a slight decline in tangent moduli values compared with lamellae densified by 10%, even though densification led to an almost linear increase in density. With the increase in lamella thickness, there is a marginal increase in the tangent moduli values.

(2) In terms of the interaction of densification and layering in two-layer materials, the highest values of tangent moduli were recorded for materials prepared with lamellae densified by 20% in both 5 mm and 9 mm input lamellae. A higher degree of densification (30 and 40%) caused a decrease in the values of the tangent moduli.

(3) The results of two- and three-layer materials composed of densified lamellae reinforced with high-strength

nonwood components did not show such a clear trend in developing the values of the observed characteristics as in the previous cases. However, it can be stated that there is a strong dependence on the change in the values of the monitored characteristics when applying high-strength nonwood components. It can be said that a nonwood component based on high-strength carbon fibers generally proves to be a more suitable reinforcement material, while components based on glass fibers have better results in a price/performance comparison.

(4) The work shows that although significantly higher density was achieved due to densification of lamellae by 30 and 40%, this fact did not signify an increase in tangent moduli values for lamellae with a minor degree of densification.

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