

Article

Bending Properties of Finger-Jointed Elements of Differently Modified Beech (*Fagus sylvatica* L.) Wood

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Abstract

The scarcity of high-quality wood encouraged the development of various technological processes for joining wood. The finger joint is one of the most widespread technological processes for wood joining. This study aimed to determine the effect of steaming and heat modification of beech wood, as well as the type of adhesive, on the mechanical characteristics of finger joints. Samples made from un-modified beech, steamed-treated, and heat-treated beech wood were bonded with polyvinyl acetate (PVAC), non-structural, and structural polyurethane (PUR) adhesives. Compressive tests on wood materials were used to evaluate their mechanical performance. The finger joint samples were tested for their bending performance. Modulus of rupture, modulus of elasticity, and compressive strength were calculated. An analysis of variance (ANOVA) was conducted to evaluate the impact of wood modification type and adhesive used on the mechanical characteristics of the finger joints. According to the results of this study, it can be concluded that the steaming process does not influence changes in the mechanical characteristics of the finger joints. Heat treatment of beech and the type of adhesive used significantly influence the tested mechanical characteristics of the finger joints and beech wood. Heat-treated beech had lower values of modulus of rupture (70 MPa) and density (690 kg/m³) and higher values of compression strength (59 MPa) in relation to un-modified (780 kg/m³) and steamed-treated (800 kg/m³) beech wood.

Keywords: wood modification; finger joint; steamed beech; heat-treated beech; polyvinyl acetate adhesive (PVAC); polyurethane adhesive (PUR); modulus of rupture; modulus of elasticity



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1. Introduction

Since ancient times, wood has been used to create many different products and constructions for various purposes, from construction elements for building structures to products necessary for everyday use. Today, un-modified wood is used relatively rarely, but through various processing methods, it is brought to a wide range of uses. The scarcity of wood as a raw material for the wood industry is evident and known worldwide. When wood was established as a high-quality natural material for low-carbon buildings, it increasingly won the favour of architects and consumers. The estimation of wood needs for new building structures, the average scenario, suggests an increase in wood consumption in 2050 that is 3.1 times higher than the volume of wood material estimated

for 2017 building constructions [1]. Considering cumulative avoided CO₂ emissions in construction procedures and carbon storage in wood lead to the expected replacement of plastic and other kinds of floors with wooden ones, a carbon benefit of 1.1 t CO₂ per m³ for every extra mass timber used [2]. The European Commission predicts that, despite the need to increase the forest carbon sink to mitigate climate change, future harvest intensity and wood utilisation will increase [3]. Even in African countries, increased wood consumption, where the growth of the population of developing countries like Nigeria, with 2.46% of the total world population, increases the use of fuel wood by about 23,787 thousand cubic meters in 10 years, due to the fact 72.3% of all energy needs come from fuel wood [4]. As interest in solid wood products grows, with the constant rise in prices and parallel constant timber quality reduction, the increasing desire to properly use raw wood material guides us in developing new wood adhesive processes [5]. Wood is most frequently used as a bonded element in producing composite wood materials, furniture, and building structures. Numerous technological solutions for the longitudinal joining of wood have been developed for the production of finger-jointed boards and furniture, as well as for the production of cross-laminated timber (CLT) or glulam (GLT) [6]. The finger joint is the most widespread technological process for the longitudinal joining of wood. The finger joint technique is an economically valuable concept for the sustainable production of furniture [7]. It ensures the use of small wood planks removed as waste [7,8]. The finger joint is one of the strongest wood joints used for structural and non-structural applications [9]. Cutting out the defects and joining even the shortest elements with finger joints increases the utilisation of raw wood almost to full capacity [10]. The main resistance of finger joints is traction parallel to the grain, followed by static bending and compression. The strength of the finger joint depends on several wood-related factors such as species, density, and natural defects as well as on processing parameters such as moisture content and temperature of wood, machining process parameters, finger geometry and its assembly pressure, adhesive type, and glueing process and pre-treatment or wood modification [9]. Finger joint geometry is almost the most important variable determining joint strength. Parameters such as teeth length, pitch, fingertip, and slope angle describe the finger's profile geometry [9]. The strength of the finger joint largely depends on the type of adhesive. Polyvinyl acetate (PVAC) and polyurethane (PUR) are the most commonly used adhesives. Polyvinyl acetate (PVAC) is a thermoplastic adhesive ordinarily destined for products used at room temperature. PVAC is a non-structural adhesive, and it is usually intended for furniture and other low-strength interior uses. Polyesters of carbamidic acid are polyurethane substances widely known for their intensive chemical reactivity, high cohesive strength, flexibility, and good performance at low temperatures [11]. PUR could be modulated as a non-structural, highly resistant, or as a structural adhesive, which is usually used in high-end furniture or for high-strength constructions.

The beech wood (*Fagus sylvatica* L.) used in this study is the most common hardwood in Bosnia and Herzegovina and Europe. Due to its good mechanical and technical properties, it is widely used in the wood processing industry (branches like producing veneer, furniture, massive wood panels, etc.) [12]. The main problem with using beech wood is colour differences due to the red heart of the beech, which puts it in an inferior position in furniture design, and it is used with caution in the furniture industry due to its high decay intensity and high dimensional change index. All wood species are affected by their moisture changes, which cause their dimensional instability, and are crucial in their use as an everyday product material. Due to this, its modification, especially those that diminish still unavoidable swelling and shrinkage, such as hydrothermal modification, plays an essential role in the strength of longitudinally bonded elements and affects the whole product. Hydrothermal treatment of wood includes a combination of moisture,

temperature, and pressure [13]. In addition to standard drying, modification treatment is often performed on beech wood, and the most common processes are steaming and thermal treatment. Thermal modification of wood is known to enhance wood's dimensional stability and biological durability by reducing moisture absorption [14]. Heat treatment (200 °C, 12 h) reduces the mass of the wood (4.8%–14.8%) and increases its darkness (52%–65%) [15]. As a result of heat treatment, the wood becomes more brittle, and its mechanical strength and technological properties decrease (0.8%–9.5%) with the level of heat treatment (100–150 °C, 4 h) [16]. Heat treatment also improves the wood's natural quality, such as resistance to biological degradation [17].

Steaming is one of the essential technological operations for pretreating beech wood. Steaming wood involves a process that alters its physical and mechanical characteristics [18]. The practice of steaming wood began primarily to even out the colour, especially in wood with an irregular heartwood. In this process, wood is exposed to saturated water vapour, causing it to heat up and change its properties [5]. The effects of wood steaming primarily influence the content of extractives and holocellulose, with minimal impact on cellulose and lignin. Although the amounts of cellulose and lignin remain unchanged, the crystallinity of cellulose increases during steaming, resulting in minor structural changes to the lignin macromolecule [19]. This increase in cellulose crystallinity can potentially stabilise the wood's form, as the portion of amorphous cellulose responsible for dimensional changes is smaller.

This study investigated the effects of beech wood treatments and the use of different adhesives on the mechanical properties of finger-jointed elements. The aim was to determine the modulus of rupture (MOR) and modulus of elasticity (MOE) of untreated and treated (heat treatment and steaming treatment) beech wood finger-jointed with two types of adhesive (PVAC and PUR).

2. Materials and Methods

All investigations were conducted on beech wood (*Fagus sylvatica* L.), a standard wood commonly used for making furniture, wood products, and finger-jointed boards, as well as for many standard tests in wood technology. With two types of today's standard industrial wood modification processes, three types of wooden materials were obtained and used to test the modulus of elasticity in bending and bending strength. Un-modified beech wood, steam-treated beech wood, and heat-treated beech wood elements with dimensions 350 × 45 × 45 mm were used to make samples in the experimental investigation. Un-modified beech wood was obtained from commercial logs, standardly dried. Steamed elements were obtained by steam treatment in an industrial direct steamer with the usual industrial procedure at a constant steam temperature of nearly 100 °C and a humidity of 98%–100% for 24 h. At atmospheric pressure, the temperature of freshly cut water-saturated wood was gradually raised in 3 steps: 40 °C for 4 h, then 60 °C for 5 h, and 80 °C for 4 h. The remaining 12 h, it stays at 100 °C. Steamed wood was dried to a standard 8%–10% moisture content. Heat treatment was performed in a vacuum heat treatment chamber, starting with pre-heating at 100 °C for 3 h, then heated from 100 °C to 150 °C for an additional 5 h, and stayed at 150 °C for 4 h. The sample was then cooled from 150 °C to 30 °C for 12 h.

The elements were planned using a four-sided planer machine, the Weinig Powermat 400 (Tauberbischofsheim, Germany), with a 15 m/min feed speed. The wood had no visible defects, and the elements were produced in a combination of radial and tangential sections. The finger joint elements for longitudinal jointing were made on an SCM T120 milling machine (SCM Group, Rimini, Italy). The finger joint profile is shown in Figure 1a.

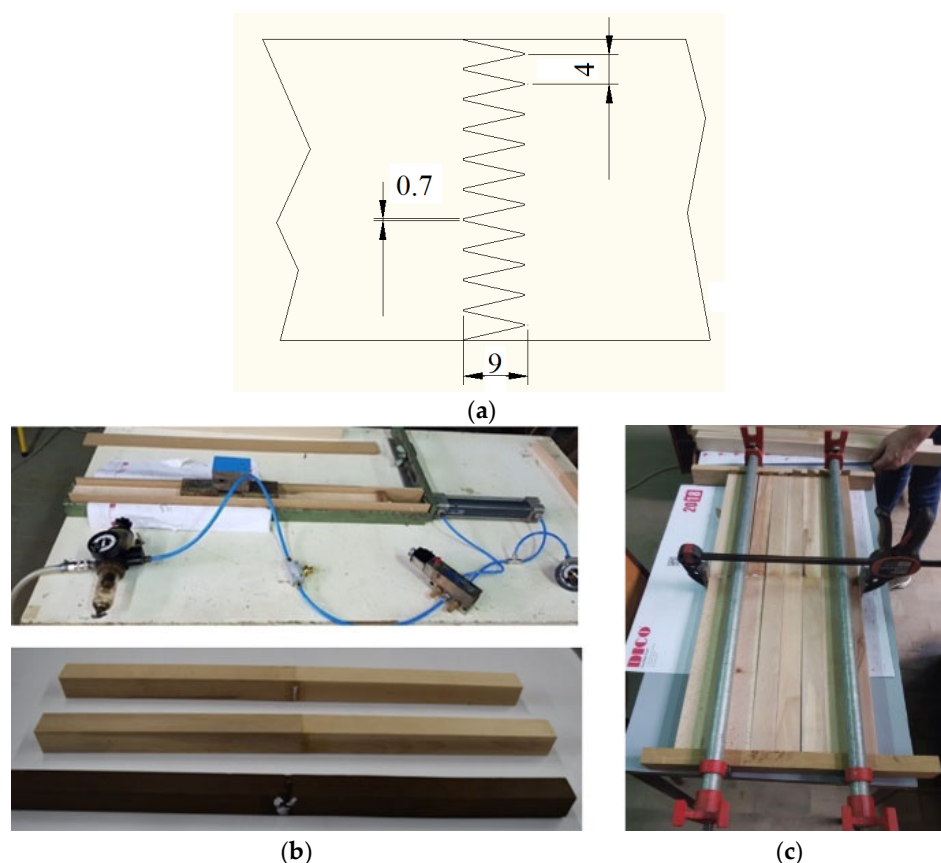


Figure 1. (a) Geometric characteristics of the finger joint; (b) Joining: handmade press (up) and finger jointed samples (down); (c) mechanical press.

The bonding process was carried out with polyvinyl acetate (PVAC) adhesive (Kleiberit 300 (KELEIBERIT SE & Co. KG, Weingarten, Germany)) and with two polyurethane (PUR) adhesives (Kleiberit 501.0 and Kleiberit 510.3.05 (KELEIBERIT SE & Co. KG, Weingarten, Germany)) under laboratory conditions. Kleiberit 300.0 is a 1-component PVAC dispersion, an adhesive that is widely used for making furniture and other products from various types of wood, including hard and exotic wood species in non-load-bearing wood products, D3 class according to EN 204 (open time 6–10 min, press time at 20 °C > 15 min, specific gravity approx. 1.10 g/cm³, white in colour, viscosity at 20 °C 12,000 ± 3000 mPa*s (Brookfield RVT, Sp. 6/20 rpm) (AMETEK Brookfield, Middleboro, MA, USA)). Kleiberit 501.0 is a 1-component polyurethane-based adhesive for non-load-bearing wood structures and products that are subjected to high loads or are temporarily exposed to increased moisture (open time 20–25 min, press time at 20 °C and 65% relative humidity 20 min, specific gravity approx. 1.13 g/cm³, brown in colour, viscosity at 20 °C 7000 ± 1500 mPa*s (Brookfield RVT, Sp. 6/20 rpm)). Kleiberit 510.3.05 is a 1-component polyurethane-based adhesive intended for finger joint bonding of load-bearing wood components (open time < 5 min, press time at 20 °C and 65% relative humidity, 20 to 100 min dependent on adhesive thickness, specific gravity approx. 1.13 g/cm³, white to yellowish colour, viscosity at 20 °C approx. 18,500 mPa*s (Brookfield RVT, Sp. 6/20 rpm)), highly resistant to heat (EN 14257) and achieves very high strength values. Although this glue is not used in the production of furniture and other everyday wood products, it was included in the research to emphasise the influence of high-quality glue on the studied properties. Joining was performed using a hand-made pneumatic press to join all the individual element pairs, with the same pressure to the final sample measurement of 700 × 40 × 40 mm (Figure 1b). After short jointing in the pneumatic press, elements were put in a mechanical press to hold them with no

additional pressure added during the curing process of the adhesive. Table 1 shows the bonding parameters for all adhesives, including pressure, pressing time, glue spread rate, and curing time.

Table 1. Bonding parameters.

Bonding Parameters	Values
Pressure imposed in a handmade press (bar)	3
Pressing time-handmade press (sec)	4
Pressing time-mechanical press (min)	40
Glue spread rate (g/m ²)	140–180
Curing time (day)	7

This way, nine groups were formed (3 types of adhesive $\times$ 3 types of wood), each containing 30 elements. The elements are labelled with a letter indicating the type of material (UB-un-modified beech, SB-steamed beech, and HTB-heat treated beech). The number indicates the types of adhesive used (1—PVAC adhesive (Kleiberit 300), 2—PUR adhesive (Kleiberit 501.0), and 3—PUR adhesive (Kleiberit 510.3.05); for example, UB1 represents un-modified beech with PVAC adhesive).

The elements were conditioned at 20 ± 2 °C with a relative humidity of $60\% \pm 5\%$ for seven days. The moisture content and density of the wood in the finger joint elements were determined according to standard ISO 13061-1 and standard ISO 13061-2, respectively. The results of the physical properties determined for the wood elements are presented in Table 2.

Table 2. Average moisture content and density of wood.

	Moisture Content, %			Density, kg/m ³		
	Average	Stdev	CoV	Average	Stdev	CoV
Un-modified beech	13.05	0.35	2.66	780	35.86	4.59
Steamed beech	13.28	0.21	1.61	800	28.65	3.45
Heat treated beech	3.42	0.36	10.46	690	32.92	4.79

It is a well-known fact that the aforementioned modification treatments are used to increase durability and reduce dimensional changes caused by moisture in wood, which, due to natural processes, is constantly absorbed or released depending on climatic variations. Therefore, this paper examines how these processes affect the mechanical properties of the finger joint. To distinguish the influence of changes in the mechanical properties of wood from those that occur due to the bonding of different materials, it is necessary to determine the differences in mechanical properties caused by the modification. This understanding is crucial for assessing the impact of various adhesives on the changes in the bonded joint itself when applied. Therefore, modulus of elasticity in bending, bending strength, and compression stress parallel to the grain of un-modified, steam-treated, and heat-treated beech wood elements were determined for compact wood elements. The modulus of rupture (MOR) in static bending was determined according to the standard BAS ISO 13061-3. The measured deflection of the beam shown in Figure 2 was used to determine the apparent value of the elasticity modulus, as a simplified procedure based on the BAS ISO 13061-4 standard. Ultimate stress determination in compression parallel to the grain was performed according to the standard ISO 13061-17 with specimens of $20 \times 20 \times 40$ mm.

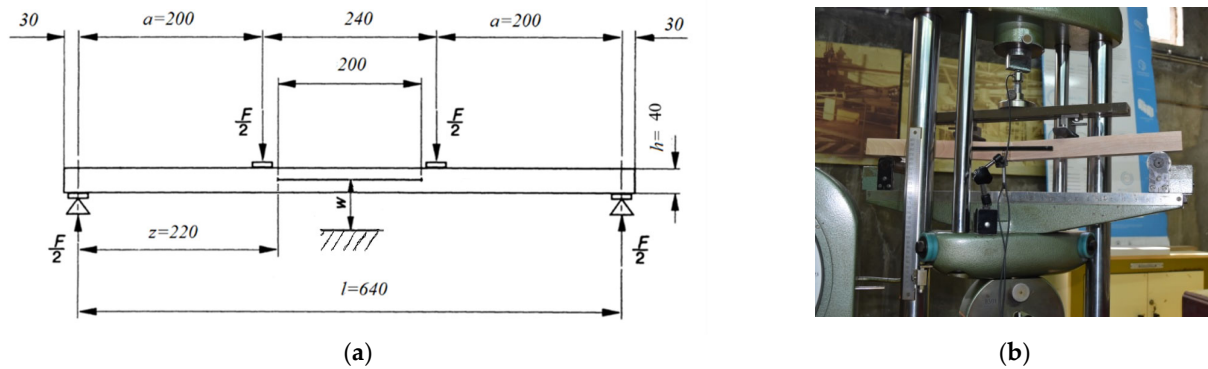


Figure 2. The test setup with dimensions in mm (a) and experimental determination (b) of modulus of rupture and modulus of elasticity in bending.

The same bending tests shown in Figure 2 were conducted on finger-jointed elements. During the testing, the finger joint was positioned on the lateral side of the samples (horizontal orientations of finger joints). The apparent value of the elastic modulus was calculated using a new method based on the basic differential equation of the elastic curve from beam deflection analyses compiled into Equation (1) [20], while the MOR was determined according to Equation (2).

$$E = \frac{(F_2 - F_1) \cdot l^3}{12 \cdot (w_2 - w_1) \cdot \frac{b \cdot h^3}{12}} \cdot \left\{ \frac{z}{l} \cdot \left[3 \cdot \left(\frac{a}{l} \right) - 3 \cdot \left(\frac{a}{l} \right)^2 - \left(\frac{z}{l} \right)^2 \right] + \left(\frac{z - a}{l} \right)^3 \right\} \quad (1)$$

$$f_m = \frac{3 \cdot a \cdot F_{max}}{b \cdot h^2} \quad (2)$$

Tests were carried out in the Laboratory for Composite Materials at the Faculty of Mechanical Engineering in Sarajevo. Laboratory conditions were as follows: air temperature, 20 °C; and relative humidity, 65%. The mechanical properties were tested on a universal testing machine (Zwick-Type 1282 (Zwick Roell GmbH & Co. KG, Ulm, Germany)). The displacement velocity during tests was maintained at 8.0 mm/min. The equipment and software that were used to collect, analyse, and visualise the results of the measure are a force sensor (HBM U9C, 10 kN), a displacement transducer (HBM W110), a QuantumX data acquisition system (DAQ), and CATMAN data acquisition software, all from Hottinger Brüel & Kjaer GmbH, Darmstadt, Germany.

Fracture analysis and estimation of the main failure patterns were conducted across the entire surface of the four lower fingers, which were subjected to tensile forces. Fracture and joint breaking surface analyses were performed using a visual method. Detailed examinations were carried out with optical microscopy using a Mitutoyo TM-505 (Mitutoyo Corporation, Kawasaki City, Japan) toolmaker microscope and an HDMI6MDPX high-resolution camera.

Statistical analysis and data visualisation were performed using the Statistica software (StatSoft GmbH, Hamburg, Germany). Analysis of variance (ANOVA) was used to evaluate the variation of the MOE in bending and the MOR of samples grouped by the type of wood and the adhesives used. Levene's test checked the homogeneity of the variances, and the Shapiro-Wilk test confirmed the normality of the data. If the one-way ANOVA proved statistical significance, a Tukey pairwise comparison (post hoc) test was performed. The effect sizes of the pairwise test were estimated using Holm-adjusted *p*-values. The presence of significant differences between the compared results, as presented in the tables with no differences, was marked with an "X" on them. Graphic displays were made using whiskers,

and bar plots were used. Descriptive statistics were also used to display the results on graphs. All results show a 95% family-wise confidence level.

3. Results and Discussion

The results of the mechanical properties of the un-modified and treated beech wood elements are shown in Figure 3.

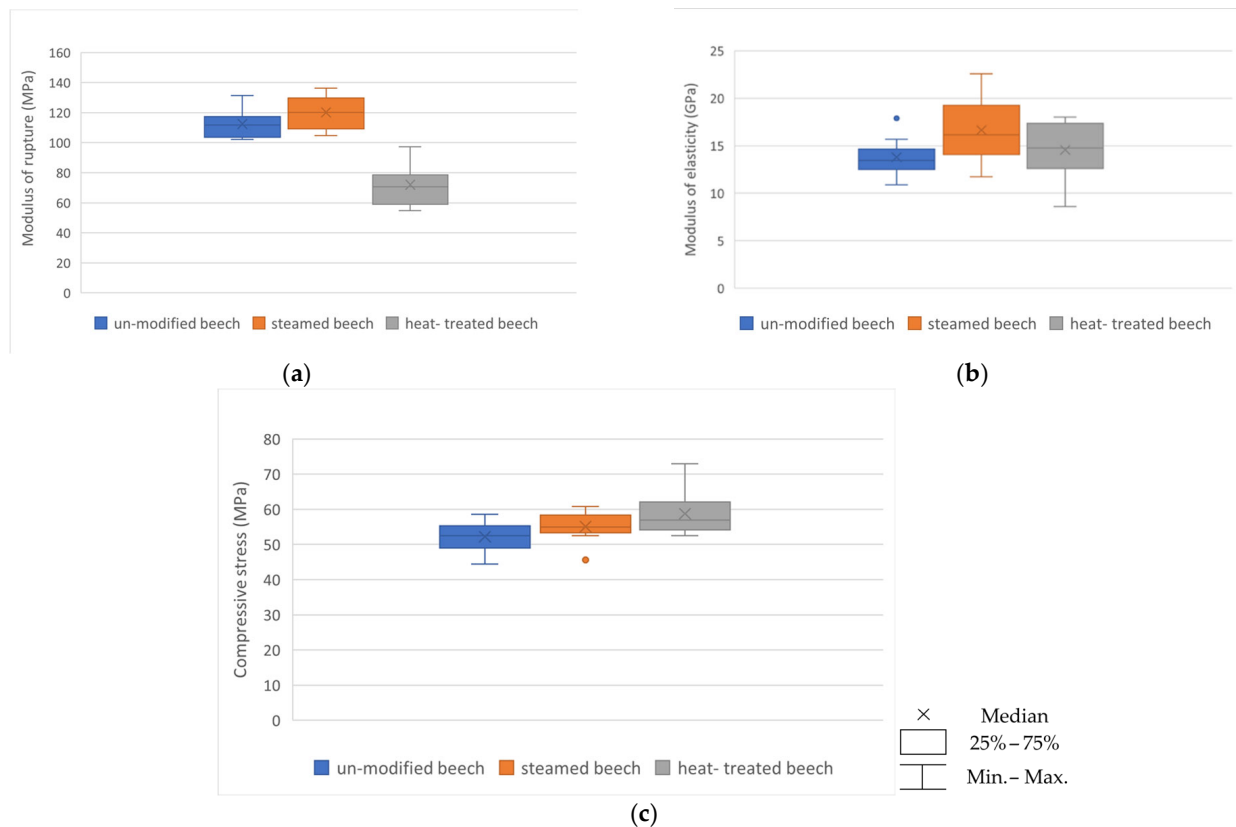


Figure 3. The effect of wood modification on the mechanical characteristic (whiskers show 5th–95th percentile): (a) Modulus of rupture; (b) Modulus of elasticity; (c) Compressive stress.

One-way ANOVA was performed on the results of the types of wood to compare the influence of thermal modification and the steaming process on the changes in mechanical characteristic properties of the wood. Results obtained by ANOVA show no statistically significant difference in the mean values of modulus of elasticity between un-modified beech, steam-treated beech, and heat-treated beech ($p = 0.137$). However, in the case of MOR, there was a statistical difference in results obtained for the comparison of un-modified beech and heat-treated beech, as well as for the comparison of steam-treated beech and heat-treated beech. Results obtained for un-modified and steam-treated beech do not show statistically significant differences. Similar results with no significant difference in the beech wood steaming process on compressive stress can be noticed in Figure 3c. This confirms that wood steaming has a minor influence on mechanical properties, as expected. These results also show that the heat-treatment of beech wood, as an intensive process, influences changes in bending strength. Compared to un-modified and steam-treated beech, lower MOR values were obtained for heat-treated beech, with a decrease of about 35%. Heat treatment of beech wood also influences changes in compressive stress (Figure 3c and Table 3) with a 10% higher value for heat-treated beech than un-modified beech. These results are in accordance with research on changes in beech wood under the influence of the

heat treatment process, where a significant degrading effect was observed on hemicellulose and lignin, causing a loss of its mechanical properties [21].

Table 3. The correlations between un-modified (UB), steam-treated beech (SB), and heat-treated beech (HTB) for modulus of rupture and compressive stress.

Modulus of Rupture			Compressive Stress		
SB	HTB	UB	SB	HTB	UB
0.493	0.001	UB	0.452	0.024	UB
	0.001	SB		0.270	SB
significant at $p < 0.05$ (Tukey)					

The effects of PUR and PVAC adhesives on the finger joints' mechanical properties were determined by testing the specimens' MOR and MOE. Statistical analysis of the obtained results was used to determine trends in the modification effect of the wood elements on the mechanical properties of the finger joints bonded with PUR and PVAC adhesive. The results of the measurements of MOR and MOE in bending on elements bonded with PUR and PVAC adhesives are shown in Figures 4 and 5.

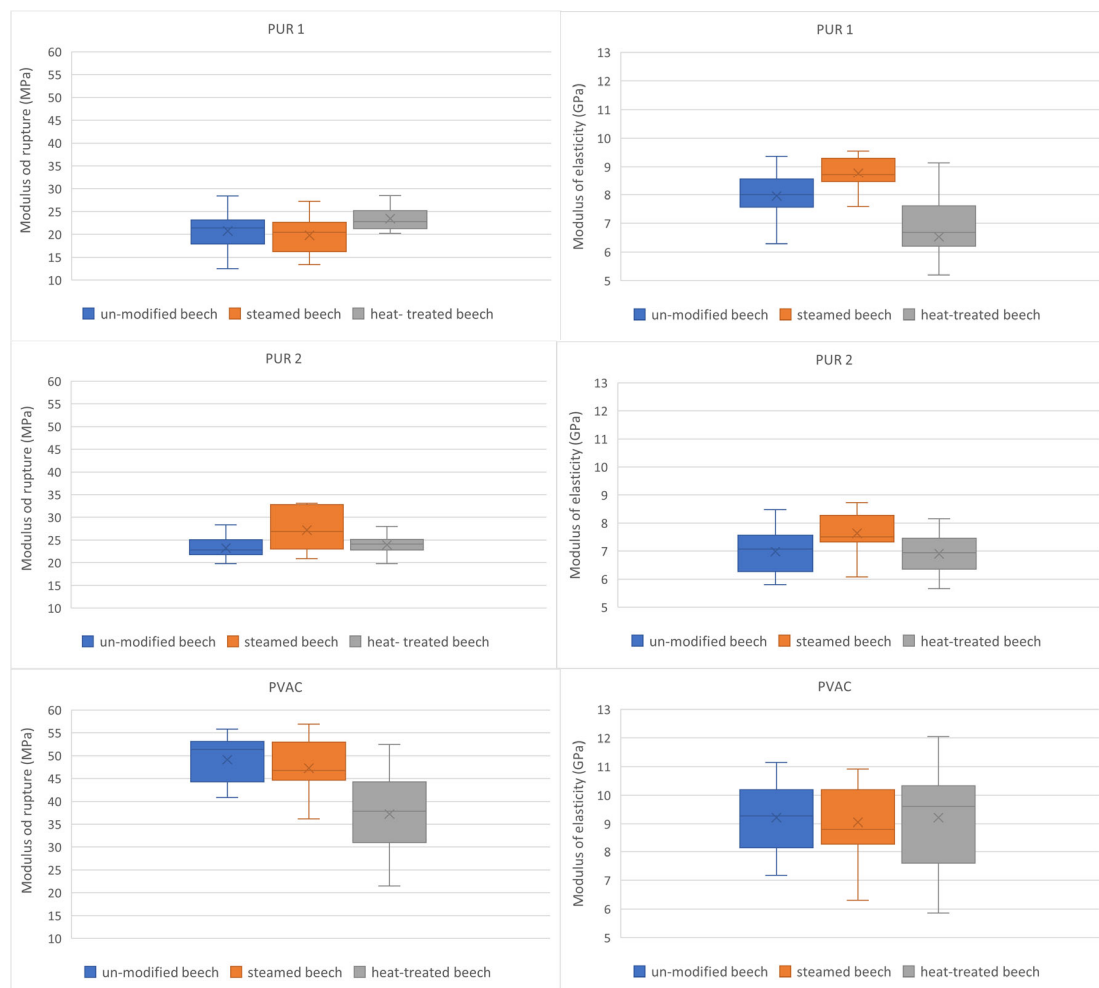


Figure 4. The effect of wood modification on the mechanical characteristics of finger joints bonded with different adhesives (whiskers show 5th–95th percentile).

One-way ANOVA was performed for each type of wood to compare the influence of the steaming process and heat treatment modification of beech wood (Figure 3 and

Table 3) on the MOR and MOE of finger-jointed elements (Table 4). There was a statistically significant difference in mean MOR ($p = 0.02$) between samples from differently treated beech wood. A Tukey pairwise comparison (post hoc) test was performed, and the test results are shown in Table 4.

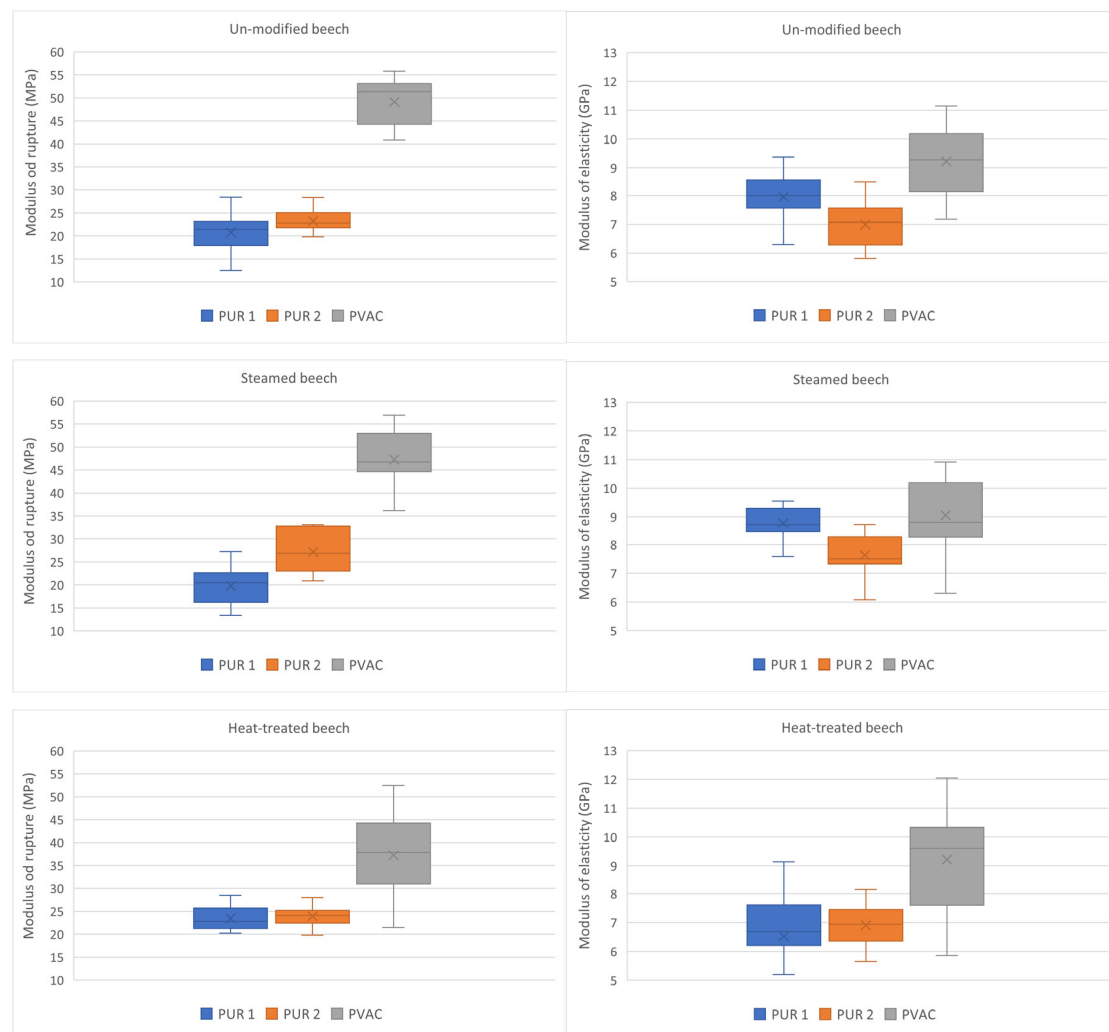


Figure 5. The effect of used adhesives on the mechanical characteristics of finger joints made with differently modified beech wood (whiskers show 5th–95th percentile).

Table 4. The correlations between un-modified beech (UB), steamed beech (SB), and heat-treated beech (HTB) for modulus of rupture and modulus of elasticity of finger-jointed elements bonded with PUR and PVAC adhesive.

Modulus of Rupture			Modulus of Elasticity		
			PUR1		
SB	HTB		SB	HTB	
0.245	0.790	UB	0.316	0.018	UB
	0.057	SB		0.001	SB
			PUR2		
SB	HTB		SB	HTB	
0.029	0.781	UB	0.051	0.979	UB
	0.125	SB		0.029	SB

Table 4. Cont.

Modulus of Rupture			Modulus of Elasticity		
PVAC					
SB	HTB		SB	HTB	
~~0.600~~	0.001	UB	~~0.996~~	~~0.997~~	UB
	0.007	SB		~~0.987~~	SB
significant at $p < 0.05$ (Tukey)					

A one-way ANOVA was also performed for each type of adhesive used to compare the influence of the adhesive on the MOR and MOE of finger-jointed elements. The results revealed an unexpected difference between the adhesives used, so they were compared and presented from a different angle in Figure 5 and Table 5 to better understand the key factors affecting joint properties.

Table 5. The correlations between finger-jointed elements bonded with Kleiberit 501.0 (PUR1), Kleiberit 510.3.05 (PUR2), and Kleiberit 300 (PVAC) for different kinds of beech wood.

Modulus of Rupture			Modulus of Elasticity		
Un-modified beech					
PUR2	PVAC		PUR2	PVAC	
~~0.054~~	0.003	PUR1	0.030	0.006	PUR1
	0.001	PUR2		0.001	PUR2
Steamed beech					
PUR2	PVAC		PUR2	PVAC	
0.001	0.001	PUR1	0.021	~~0.479~~	PUR1
	0.001	PUR2		0.001	PUR2
Heat-treated beech					
PUR2	PVAC		PUR2	PVAC	
~~0.945~~	0.001	PUR1	~~0.800~~	0.001	PUR1
	0.001	PUR2		0.001	PUR2
significant at $p < 0.05$ (Tukey)					

In this research, two key factors are identified. The first pertains to the properties of the adhesive, indicating that an adhesive with superior mechanical properties can yield better mechanical results for the joint. Our results suggest otherwise, showing that bonding wood with PVAC adhesive results in a higher MOR of joints by 40%–57% compared to samples bonded with PUR adhesive. The MOE of elements bonded with PVAC adhesive is also 5%–8% greater than that of elements bonded with PUR adhesive. This finding raises several questions, as all our knowledge suggests that PUR adhesive is superior to PVAC. This prompts a deeper analysis of joint structure. Overall, wood anatomy significantly influences this outcome, combined with the unique hardening process of PUR. The observed phenomenon can only be explained by the extensive bubble formation during the PUR hardening process, facilitated by adhesive flow into the open pores of the cross-sections in the finger joints. The microscopic views of the finger joint tooth after the bending test are illustrated in Figures 6–8. During the hardening process, a substantial portion of PUR adhesive migrates into the wood pores, leaving a small amount of adhesive filled with bubbles in a weaker adhesive layer (poor cohesion strength), which is evident in the overall cohesion failure of the joint in Figure 6a,b. This result is corroborated by a study by Bernaczyk et al. in 2022, as well as Fodor and Bak in 2023, who found that the PUR adhesive bond layer contained a significantly higher proportion of holes/voids compared to the other adhesives examined, including PVAC [22,23]. The MOR of elements bonded

with Kleiberit 501.0 adhesive is lower than that of elements bonded with Kleiberit 510.3.05 adhesive. This result can be explained by the fact that 510.3.05 is designed for load-bearing structures, necessitating greater mechanical strength and durability, along with resistance to atmospheric influences.

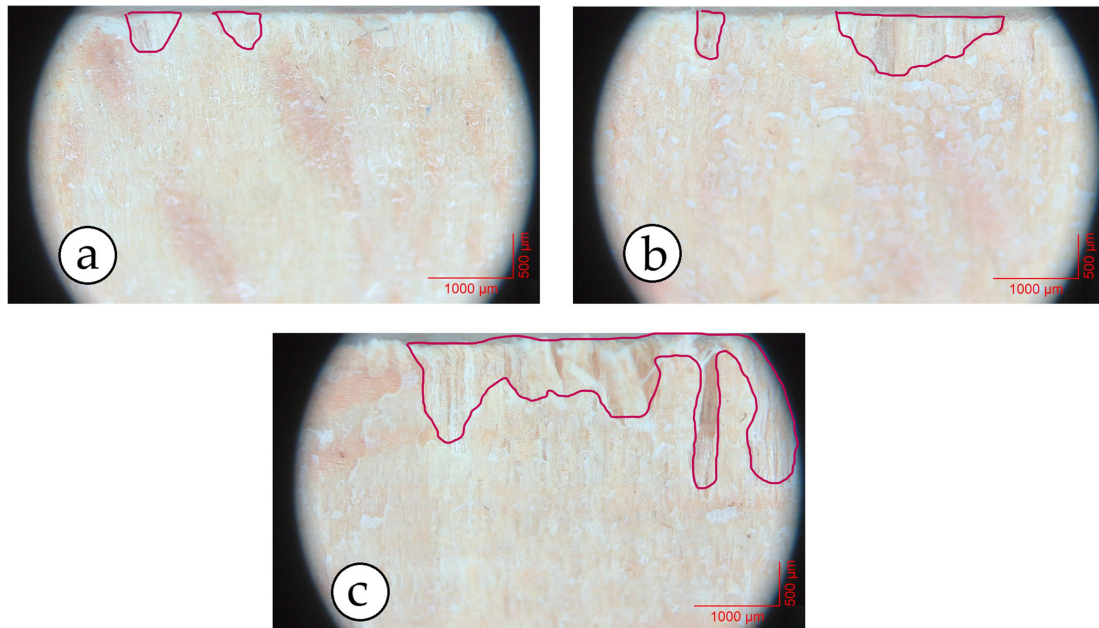


Figure 6. Microscopic views (magnification $\times 60$) of the finger joint surface with a rounded wood failure of un-modified beech after the bending test of specimens bonded with (a) PUR1 adhesive, (b) PUR2 adhesive, (c) PVAC adhesive.

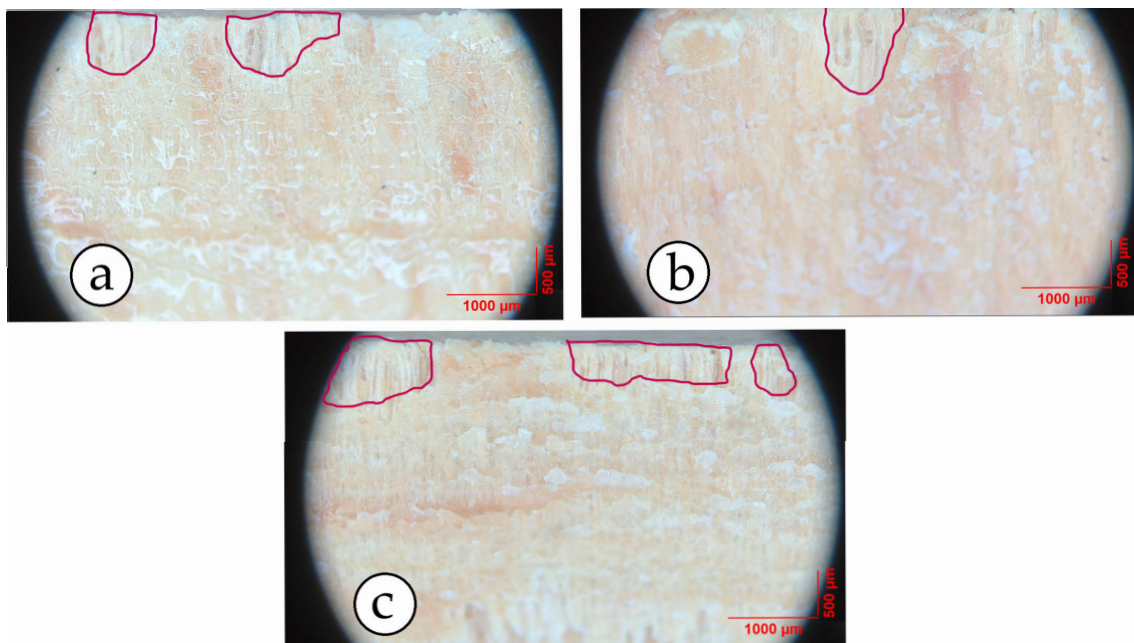


Figure 7. Microscopic views (magnification $\times 60$) of the finger joint surface with a rounded wood failure of steamed beech after the bending test of specimens bonded with (a) PUR1 adhesive, (b) PUR2 adhesive, (c) PVAC adhesive.

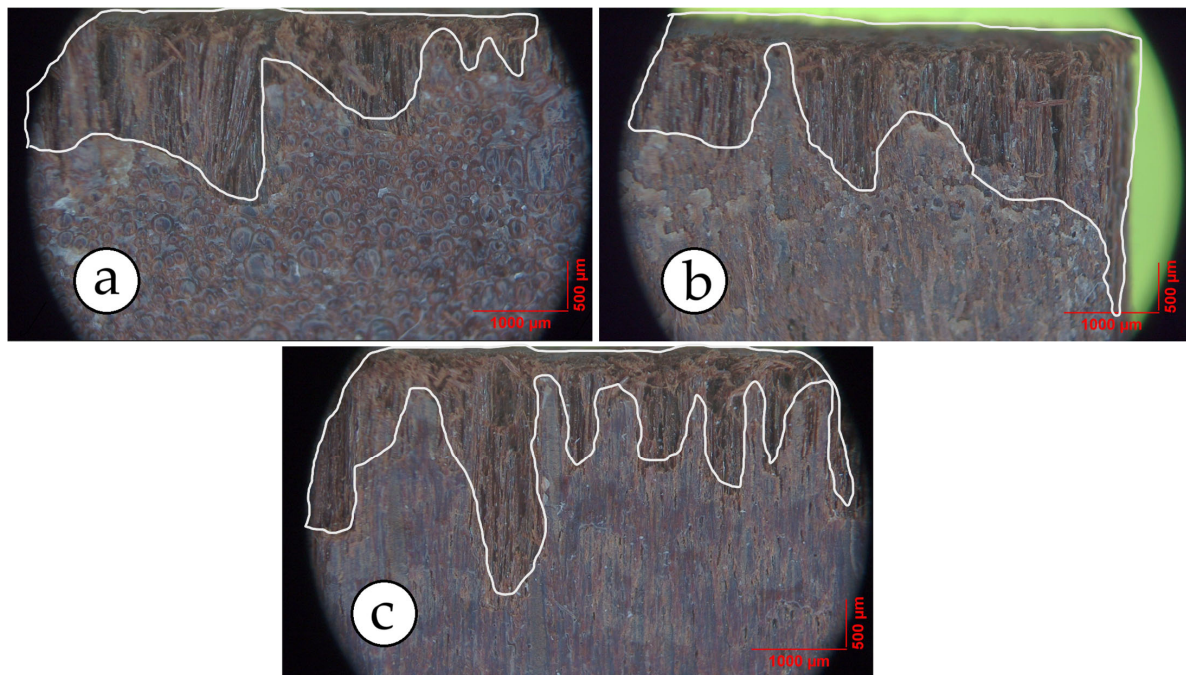


Figure 8. Microscopic views (magnification $\times 60$) of the finger joint surface with a rounded wood failure of heat-treated beech after the bending test of specimens bonded with (a) PUR1 adhesive, (b) PUR2 adhesive, (c) PVAC adhesive.

The second key factor refers to the properties of the material. From the presented results, it can be concluded that the wood steaming process only influences changes in the wood's colour and aesthetic properties of beech wood. The steaming process does not cause changes in the mechanical properties of beech wood (Table 3) or the mechanical properties of finger-jointed elements (Table 5 and Figure 5), regardless of the type of adhesive used. Heat treatment of beech wood, on the other hand, is a strong colour changer, but it also alters the wood's mechanical and physical properties (Table 3, Figure 3) as it induces chemical changes in hemicellulose and lignin [21]. This causes a decrease in density and mass, while simultaneously increasing the speed of sound and the acoustic constant [24]. It is well known that the duration of the heat treatment process at maximum temperature, wood type (fir, linden, and beech), and maximum achieved temperature (210 °C) are essential parameters that affect the retention of mechanical properties (bending and tensile) in the modification of wood [25].

This investigation shows comparable results. The mean MOR of finger-jointed elements for un-modified beech samples is approximately 19% higher than that of those made from heat-treated beech bonded with PVAC adhesive (Figure 4). In the case of steam-treated elements, the MOR results are 14% higher than those of heat-treated beech elements. This outcome was anticipated, considering that the wood modification aims not to enhance the strength of the finger joint but to minimise the dimensional changes of the wood, thereby increasing its durability.

Given the already established higher MOR of un-modified and steamed beech compared to heat-treated (Figure 3a and Table 3), this result clearly shows that MOR is the dominant factor that imposes its intensity regardless of the properties of the adhesives used (Figure 4 and Table 4), whether there is no difference in strength for PUR1 and PUR2 or the strength is significantly lower for the significantly weaker material of heat-treated wood bonded with apparently stiffer PVAC. This result contrasts with previous comparisons of PUR and PVAC adhesives, where PUR was a considerably better solution [26]. This

supports our theory that a change occurred in the bonding process, which is uncommon when bonding wood elements parallel to the wood fibre.

The results of the apparent MOE for elements bonded with PUR adhesive as a joint, with weaker bending strength, show that steam treatment influences an increase in elasticity compared to un-modified and heat-treated beech elements. However, when the PVAC adhesive is involved, no treatment affects the MOE value of the joint (Figure 4 and Table 4). Although it seems convoluted, a parallel can be drawn with the results in Figure 3b, leading to the conclusion that the adhesive significantly impacts the finger joint MOE value, as the modification does not substantially affect the beech wood material.

According to the results, when using stronger adhesive joints, only the weaker material affects the MOR (Figure 4). When using different materials in finger joints, a stronger adhesive joint brings higher MOR and a higher MOE (Figure 5).

Observing these results without analysing the failure mode could lead to incorrect conclusions, as surface fracture analysis and estimation of main failure patterns provide more information about joint bonding quality than MOR and MOE. Wood failure is common with quality glued joints and indicates that the strength of the joint (wood impregnated with glue) is greater than the cohesive strength of the wooden substrate [27]. Interface and cohesive wood failure are preferred as they are placed in the most critical part of the joint anatomy. Adhesion failure and cohesion failure in the adhesive are unfavourable patterns of joint fracture. However, adhesive failure often shows high shear strengths due to the high cohesive strength of the adhesive [28].

In the case of un-modified and steamed beech wood bonded with PUR and PVAC, the start fracture location is positioned on the lower side of the finger joint. In the samples made from heat-treated beech wood, the fracture location started on the lower side of the elements, near the finger joint. Heat-treated wood has lower mechanical characteristics than finger joints, so the wood fails first. In the case of un-modified and steamed beech wood bonded with PUR adhesive, the cohesion failure in the adhesive layer was dominant, with 90% of the failure surface showing complete finger extraction. The main reason for this can be seen in Figure 7a,b, as well as in Figure 8a,b, where a fracture surface reveals an adhesive layer filled with many small bubbles. These bubbles significantly reduced the sizes of the measuring and adhesive surfaces. Minor differences can be observed in the appearance of the fracture surface between natural and steam-treated wood; the slight variations in the volume of bubbles on the fracture surface result from the changes in wood caused by the steaming process. The failure of heat-treated beech bonded with PUR adhesive exhibits a higher proportion of wood cohesive failure, reaching up to 75% of the surface (Table 6). This aligns with the reduced strength of heat-treated wood and the decreased moisture content, which leads to fewer bubbles in the adhesive layer (Figure 8a,b), enhancing the cohesive strength of PUR adhesives.

Table 6. Fracture analysis and estimation of the main wood failure pattern.

Wood	Adhesive	Wood Failure (%)	Stdev
Un-modified beech	PUR 1	10	6.12
	PUR 2	10	6.85
	PVAC	30	15.81
Steamed beech	PUR 1	10	6.12
	PUR 2	10	5.50
	PVAC	30	15.81
Heat-treated beech	PUR 1	75	12.69
	PUR 2	75	15.81
	PVAC	40	8.33

The failure of un-modified beech (Figure 6c) and steamed beech (Figure 7c) joints bonded with PVAC adhesive had a larger portion occurring in the wood (up to 30%, Table 6). For the thermo-treated beech bonded with PVAC adhesive, wood failure and interface failure occurred almost evenly (40%/60%, Table 6), as shown in Figure 8c, representing the part of the total finger surface. This result also indicates that the properties of the wood have the most significant influence on the finger joint and that the shape of the fingers has a bigger impact than the properties of the adhesive.

4. Conclusions

The test results of the achieved mechanical characteristics indicate that the steaming modification does not affect the change in the mechanical characteristics of wood or the finger-jointed elements. Heat treatment caused changes in the wood's mechanical properties and the finger-jointed elements' mechanical characteristics. It causes a decrease in the bending strength of the material and finger joints bonded with PVAC adhesive. Concerning the use of PUR adhesives, thermal modification does not show reduced bending strength in finger joints due to the very low cohesive strength of the adhesive layer.

According to the results, bonding wood with different adhesives influences the mechanical properties of finger-jointed elements. Elements bonded with PVAC adhesive achieve the best results. Compared to PVAC, the PUR adhesive results in a 50% lower MOR for finger-jointed elements. The MOE of samples bonded with PVAC adhesive shows a similar trend, with results 5%–8% higher compared to those bonded with PUR adhesive. In general, when using stronger adhesive joints, only the MOR is affected by the weaker material used. When using different materials in finger joints, a stronger adhesive joint yields a higher MOR and a higher MOE.

Although PUR adhesives, compared to PVAC, show a superior result when gluing wooden surfaces parallel to the wood grain, in the case of longitudinal joining, the result in this investigation is exactly the opposite. The leading cause of this phenomenon is the resulting foaming of the PUR adhesive during the curing process, which, due to the enabled expansion of it into the pores of the cross-section, remains foamed in the joint with the result of a markedly reduced value of the cohesive strength of the adhesive layer. The best mechanical properties were obtained for joints made of heat-treated beech wood due to the lower relative humidity of heat-treated wood, which results in lower reactivity in contact with the PUR adhesive.

The results presented offer new insights into the use of finger joints; however, studying their durability is the next step for practical applications.

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Abbreviations

The following abbreviations are used in this manuscript:

PVAC	Polyvinyl acetate adhesive
PUR	Polyurethane adhesive
UB	Un-modified beech
SB	Steamed beech
HTB	Heat-treated beech
ANOVA	Analysis of variance

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