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Article
Experimental Research on Hybrid Hardwood Glue-Laminated Beams

Eva Šuhajdová [1,*], Pavel Schmid [2], Miloslav Novotný [1], Jan Pěnčík [1], Karel Šuhajda [1] and Ondřej Uhlík [3]

[1] Institute of Building Structures, Faculty of Civil Engineering, Brno University of Technology, Veveří 331/95, 602 00 Brno, Czech Republic
[2] Institute of Building Testing, Faculty of Civil Engineering, Brno University of Technology, Veveří 331/95, 602 00 Brno, Czech Republic
[3] Institute of Computer Aided Engineering and Computer Science, Faculty of Civil Engineering, Brno University of Technology, Veveří 331/95, 602 00 Brno, Czech Republic
* Correspondence: suhajdova.e@fce.vutbr.cz; Tel.: +420-541147446

Abstract: The aim of this work was to verify the behavior of hybrid hardwood glue-laminated beams and the possibility of replacing Norway spruce (*Picea abies*) construction elements, especially in roof and ceiling structures. The samples were six lamellae homogeneous beech (*Fagus sylvatica*) beams and six-lamellae hybrid beech-poplar (*Fagus sylvatica–Poplar* spp.) beams; each beam had a cross-section of 60 × 120 mm and was glued with polyurethane adhesive. The samples were loaded using destructive four-point bending tests according to EN 408; the obtained bending strength and modulus of elasticity were statistically evaluated and compared to each other in both types of samples. The results showed that the examined properties of the hybrid beams (with a 16% weight reduction) are comparable to the properties of homogeneous beech glue-laminated beams. Based on the obtained data, the timber elements that are currently used can be successfully replaced by hardwood glue-laminated elements. Based on their higher load-bearing capacity, the cross-section depth can be reduced compared to a larger cross-section depth in spruce beams; this means that hardwood could be suitable in building renovations.

Keywords: beech wood; bending strength; hybrid hardwood glue-laminated beam; modulus of elasticity; poplar wood

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1. Introduction

The majority of glue-laminated timber (glulam, GLT) in Europe is produced from softwood, mainly Norway spruce (*Picea abies*), and the existing standards, gluing systems, and sawmill equipment are set for the manufacturing of such wood types [1,2]. The gradual decrease of spruce covered areas in the forests of Europe and the increase in areas covered in hardwood, especially beech (Fagus sylvatica), indicates that the latter will become the local sustainable source of hardwood in Central Europe. Therefore, the properties of hardwood elements need to be sufficiently tested and the test results should contribute to updating the current standards (building code), and therefore, it will be possible to make use of the full potential of hardwood and develop quality hardwood products.

Compared to softwood, hardwood has a higher load-bearing capacity, which can be a significant factor when producing highly stressed timber structures especially for large spans. The excellent mechanical properties of hardwood are also reflected in the inclusion of hardwood in the high-strength classes. On the other hand, hardwood has a relatively high density compared to softwood. Another limitation of hardwood, especially beech wood, is its relatively high shrinkage/swelling coefficient, which may increase the risk of delamination of the glued joints. For that reason, hardwood bonding is no trivial task. Hardwood often shows different behavior when glued [3–5] because of its different structure, wood chemistry [6], and extractive content [7] compared to softwood. Hardwood also has a higher susceptibility to swelling and shrinkage (especially beech wood) [1],and a higher bearing capacity than softwood, and therefore, the loads the glue needs to transfer are very high [2,8]. Due to its low natural durability, the use of beech glulam is restricted to service class 1 [9] as defined in EN 1995-1-1 [10].

There is no building standard specified for hardwood glue-laminated timber in Europe and certainly not for GLT comprised of timber obtained from different wood species. It is possible to partially follow the standard regulations for softwood [11,12], although some production requirements may not be suitable for hardwood applications [13]. It is also possible to follow some national regulations (particularly [14]). It is possible to classify hardwood based on the standards EN 14081-1 [15] and EN 1912 [16] or DIN 4074-5 [17]. The production of hardwood glue-laminated elements is possible, but in order to do so, it is necessary to have the approval of a certificate issuing institution. In order to obtain approval, it is possible to classify GLT into strength classes according to EN 338 [18] using the characteristic values determined according to EN 384 [19].

The aim of this research was to show the potential of timber obtained from wood species that are locally available. Thanks to extensive research, timber from these wood species could become a new source of material for the production of GLT and other related products [1]. Beech wood appears to be the most suitable among the local wood species for the use in load-bearing elements because of the expected increase in beech-covered areas, its straight grain with a low occurrence of knots, and its comparable mechanical properties to a more expensive oak [20]. The disadvantages of beech wood e.g. its relatively high shrinkage/swelling can be reduced by using it in glue laminated and cross-laminated elements that are used in environments with low humidity fluctuations. The great potential of its use for structural purposes is described in the literature [21] which deals with combined beech glulam beams, where the cross-section consists of beech wood of different strength classes.

Due to the relatively high density of beech wood, the use of homogeneous beech elements brings certain drawbacks, e.g., worse handling in construction sites, more expensive transport, etc. In order to achieve a reduction in weight, another type of wood was used in order to reduce the weight of the element. Reducing the weight of hardwood elements is achieved by replacing some of its lamellae with softwood lamellae. The above-mentioned method is described in the literature, e.g., in [8,22,23].

In [22] Blaß and Frese examined the behavior of 10-layer GLT members with a cross-section depth of 300 mm made from a combination of hardwood and softwood. When beech timber was used in the top and bottom zone (i.e., the outer layers), it was found that the combined elements only showed a slightly lower bending strength than beams made entirely of beech. The 10-layer GLT beams could be classified into classes GL28 up to GL48 according to EN 14080 [11].

Muraleedharan and Reiterer [8] examined the bending strength and modulus of elasticity of five-lamellae glulam beams made of oak and spruce. Different lamellae layups in the cross-section were examined. The cross-section of the tested beams was 120 × 135~200 mm. The experiments were complemented with FEM analysis. The results showed that the performance of glue-laminated timber can be increased by a combination of hardwood (oak) and softwood (spruce) lamellae compared to homogeneous softwood.

Sciomenta et al. [23] performed an experimental investigation on eight-layer homogeneous (beech only) and hybrid (beech–Corsican pine) glulam beams with a cross-section depth of 144 mm. The used lamellae had no finger joints and were 18 mm-thick. The experiments were complemented with numerical simulations and the results showed the high mechanical performance of the examined beams, both the homogeneous beams and the hybrid beams. The homogeneous beams reached a 7% higher maximum force than the hybrid ones and a bending stress 8.3% higher than the hybrid ones.

The price of spruce wood has been increasing, mainly due to the bark beetle calamity. Therefore, there is an ongoing effort to decrease the weight of the elements using other species than spruce wood and to use wood that is not sought after and whose price does not increase. A hybrid beam was designed using soft, low-density poplar timber in the inner zone of the beam. Poplar wood has similar properties to spruce; it has low strength parameters. The good availability of poplar wood in Central Europe (including its fast growth), low density, easy workability, and easy gluing [24] were key factors for the choice. Its shrinkage/swelling coefficient is lower than beech wood, but higher than softwood [6,25]. It is assumed that the effect of a different shrinkage/swelling coefficient for beech wood compared to poplar wood can be partially eliminated using hybrid beams in service class 1. The effect of humidity on the behavior of hybrid beams will be analyzed in further research.

The use of poplar wood in load-bearing elements is mentioned in the literature, especially in the field of research on cross-laminated timber (CLT), where poplar wood is either used separately [26–28] or combined with pine, fir [29], beech [30]. Apart from the above-mentioned studies, there are several others, esp. Timbolmas et al. [31] in which hybrid pine–poplar glulam beams were subjected to bending. Pine was used for the outer layers was used poplar for the inner layers of the six-lamellae beams. It was discovered that the composite layups made of pine and poplar showed high stiffness, closer to that of the beams made from pine lamellae and much higher stiffness than the poplar glulam beams. In addition, the density of the pine–poplar specimens underwent a 17% increase with respect to the poplar specimens. In another study [32], poplar was combined with eucalyptus in seven-layer glue-laminated beams, and they demonstrated good performance and structural efficiency.

Based on our literature research, it is assumed that:

- A glued element from a combination of several wood species can be functional;
- It is possible to combine beech and poplar wood in one element;
- Decreasing the weight of an element in the inner zone should not have a major effect on its bearing capacity.

In addition to verifying these assumptions, the aim of this paper is to verify whether the gluing of beech and hybrid elements using PUR adhesive is suitable since the researchers used different adhesives in most of the above-described studies (e.g., [2,3,13,22,23,32]). In study [7], PUR adhesive was used for gluing hardwood glulam members that were thermally loaded and that then underwent bending tests. In addition, gluing beech and poplar wood with PUR adhesive has not yet been described in the literature.

2. Materials and Methods

2.1. Materials

In this study, European beech (*Fagus sylvatica*) and poplar (*Populus*) timber purchased from a local sawmill were used. In total, 24 pcs of testing bodies with dimensions of 60 × 120 × 2400 mm were produced (semi-scale samples); each beam consisted of six 20 mm-high lamellae (Figure 1). There were two types of testing bodies:

- The homogeneous glue-laminated timber (h)—testing bodies were made from beech timber (marked BE (h));
- The hybrid glue-laminated timber (hyb)—testing bodies were made from beech and poplar timber (marked BE-PO (hyb)).

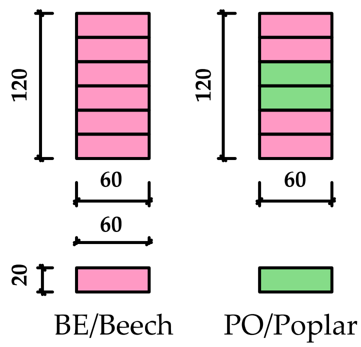

Figure 1. Tested samples GLT: BE = beech, PO = poplar. Dimensions in mm.

As shown in [2], finger joints with the commonly used geometry reduce the bearing capacity of the element and are unsuitable for beech glue-laminated timber. The dominant role of finger joints in the failure of beech glulam timber is also stated in the literature [21]. A study [33] asserts the need to optimize the geometry of the finger joints, especially for beech glulam of higher strength classes (GL 55). A different finger joint geometry was suggested in [2], but the manufacturers in the Czech Republic were unable to implement it. Since this study focuses on the behavior of GLT beams as a whole, lamellae without finger joints were used for the production of the glued elements. Therefore, the experiment results are not affected by the operability or inoperability of the finger joint (the finger joint research was conducted in a previous study [34]).

The production of the testing bodies was provided by the supplier Roman Million Wood s.r.o., Moravská Třebová, Czech Republic, which specializes in the production of glue-laminated timber and glue solid timber [35]. PUR adhesive Casco Adhesives Polyurethane system 2010 by the Swedish manufacturer AkzoNobel [36] was used for gluing the GLT lamellae. It is a single component adhesive used for gluing solid timber beams, glue-laminated beams, finger joints, and construction elements, such as cross-laminated timber (CLT), always with a requirement for high resistance against water and climatic conditions.

The adhesive was machine applied in the amount of approx. 180–200 g/m^2; the open assembly time was 10–15 min. The applied pressure was 1 N/mm^2 and the pressing time was 120 min (due to a lack of experience with the combination of the chosen adhesive and material, the extended pressing time was chosen for safety reasons: the pressing time required by standard [11] is in the order of seconds). Photographs from the production of the testing samples are shown in Figure 2.

(**a**) (**b**)

Figure 2. Production of GLT: (**a**) adhesive application and (**b**) beam arrangement in the press (authors' archive).

The density of the timber was determined from single non-glued lamellae according to standard ČSN 49 0108 [37]. Density determination tests were performed on the set of specimens intended for the lamellae bending tests described below. The tests were performed with the remaining lamellae that had not been used for the production of GLT beams. From the total amount of beech and poplar leftovers, it was possible to create a total amount of 29 samples. Twenty of these samples were poplar lamellae and nine were beech lamellae. The samples were adjusted to a length of 380 mm and the cross-section was not adjusted and corresponds with the 60 × 20 mm lamellae cross-section in the GLT beams. None of the samples tested had knots or faults. In addition, spruce lamellae of the same dimensions were also tested for comparison (20 pcs in total). The average density of the studied beech timber at 12% moisture content was 727 kg/m^3, the average density was 394 kg/m^3 for the poplar timber, and the average density was 454 kg/m^3 for the spruce timber.

The density of the glulam testing bodies was determined from pieces cut from the testing bodies. The number of samples for determining the density of GLT corresponded to the number of GLT beams. The average density at 12% moisture content of the BE (h) samples was 723 kg/m^3, and for the BE-PO (hyb) samples, it was 605 kg/m^3.

In order to determine the mechanical properties of the timber, which was used for producing the glued beams, tests of non-glued lamellae were performed as well. The tests were also carried out on spruce lamellae for comparison. The tests mentioned above were performed on a set of samples that had already been used for density determination.

2.2. Methods

The experiments for testing the properties of GLT beams from hardwood focused on the behavior of the beam as a whole. The determined properties included the strength and modulus of elasticity according to standard EN 408 [38]. The scheme of the test arrangement is shown in Figure 3.

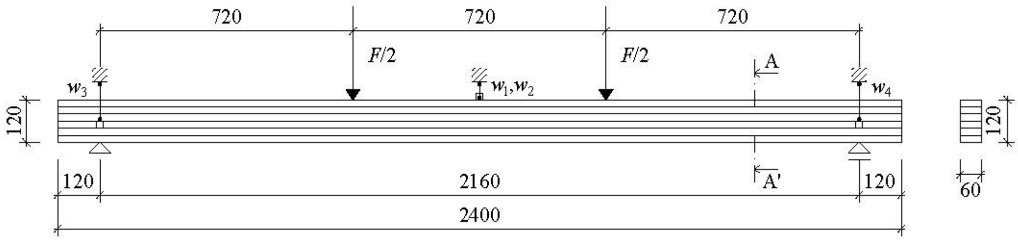

Figure 3. Geometry of the GLT beam test in the four-point bending test. Dimensions in mm.

In order to monitor the deformation w, the beams were equipped with Ld HBM inductive displacement transducers placed on steel L profiles, which were mounted on beams with screws at the points of supports and in the middle of the span (marked w_1 to w_4). The position of the sensors is shown in Figure 4.

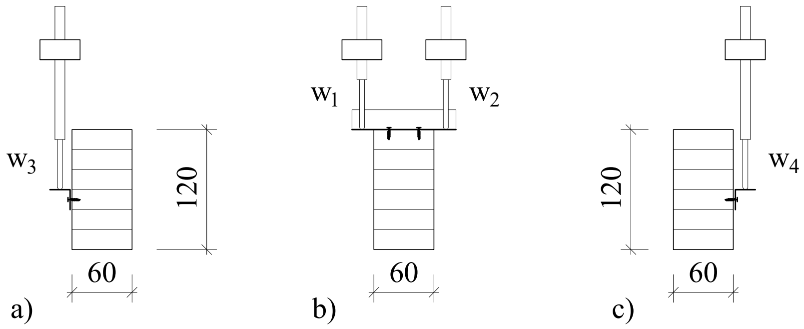

Figure 4. The position of displacement transducers on the testing sample and the position of the cross-sections corresponding to Figure 3: (**a**) at the left support, (**b**) in the middle of the span, and (**c**) at the right support. Dimensions in mm.

Loading was performed with the use of an INOVA electrohydraulic loading system, on a breaking track in the AdMaS Center (Figure 5) at a constant speed of 3.6 mm/min, and the bodies were loaded up to the point of failure. During the test, loading F (in N), deformation w (in mm), and time t (in s) were recorded. On the basis of the recorded values, bending strength f_m and modulus of elasticity $E_{m,l}$ were determined according to Equations (1) and (2).

$$f_m = \frac{3 \cdot F_{max} \cdot a}{b \cdot h^2}, \tag{1}$$

$$E_{m,l} = \frac{a l_1^2 (F_2 - F_1)}{16 I (w_2 - w_1)}, \tag{2}$$

where F_{max} is the maximum force (in N); h, b is the cross-sectional depth and width (in mm); a is the distance between the point of application of the load and the nearest support (in mm), $a = 5h$; l_1 is the measured length (in mm) to determine the modulus of elasticity; $F_2 - F_1$ is the load increase (in N) on the regression line with a correlation coefficient of 0.99 or better; $w_2 - w_1$ is the deformation increase (in mm) corresponding to $F_2 - F_1$; and I is the moment of inertia of the cross-section in mm^4.

Figure 5. Test of the GLT testing body in the four-point bending test (authors' archive).

Since the testing bodies were not conditioned in a standard environment with a temperature of (20 ± 2) °C and a relative humidity of (65 ± 5)%, the moisture content of the samples was not the required 12% but ranged around 8%. The obtained values of the bending strength and modulus of elasticity of the tested samples were adjusted for values corresponding with a 12% moisture content $f_{m,12}$ and $E_{m,12}$ according to the standards [19,39,40].

The determined values for the bending strength and modulus of elasticity for the homogeneous beech and hybrid beech-poplar glue-laminated beams were evaluated with an unpaired two sample t-test under the assumption of equal variances. p-values < 0.05 were considered significant. In addition, a normality test (Shapiro–Wilk) and a two-sample variance equality test (Levene's test) were used.

The lamellae, from which the glue-laminated beams were made, were tested individually. The tests included strength tests and modulus of elasticity tests in a four-point bend. The tests were performed in accordance with standard EN 408 [38]. Loading was performed with a Heckert FPZ 100/1 mechanical press. The bodies were loaded up to the point of failure.

Deformation w was monitored using a fixture. During loading, the fixture was secured to the testing body above one of the supports, and in the middle of the span. An Ld HBM displacement transducer (type WA/100 mm) was placed above the other support. During the deflection of the testing body, the double vertical displacement $2w$ above the support was measured by the transducer (Figure 6).

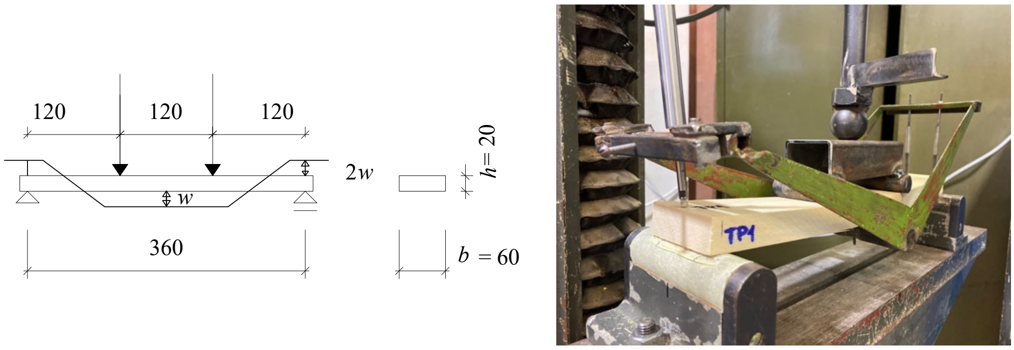

Figure 6. Arrangement of the test for strength and the modulus of elasticity in the lamellae bending test. Dimensions in mm.

The determined bending strength and modulus of elasticity were converted to values corresponding with a 12% wood moisture content according to [19,40].

The lamellae test results were statistically evaluated. Statistical significance was calculated by the Kruskal–Wallis test, as the test does not require the groups to be normally distributed or to have equal variances. The significance level for all tests was set to a value of 0.05. In addition, a normality test (Shapiro–Wilk) and a two-sample variance equality test (Levene's test) were used. Subsequently, the Dunn's multiple comparison test was used to identify which specific mean values were different from the others.

3. Results

3.1. Load-Bearing Capacity and Failure Modes

The relationship between the force F and the deformation w for all of the tested elements is displayed in a single graph (Figure 7).

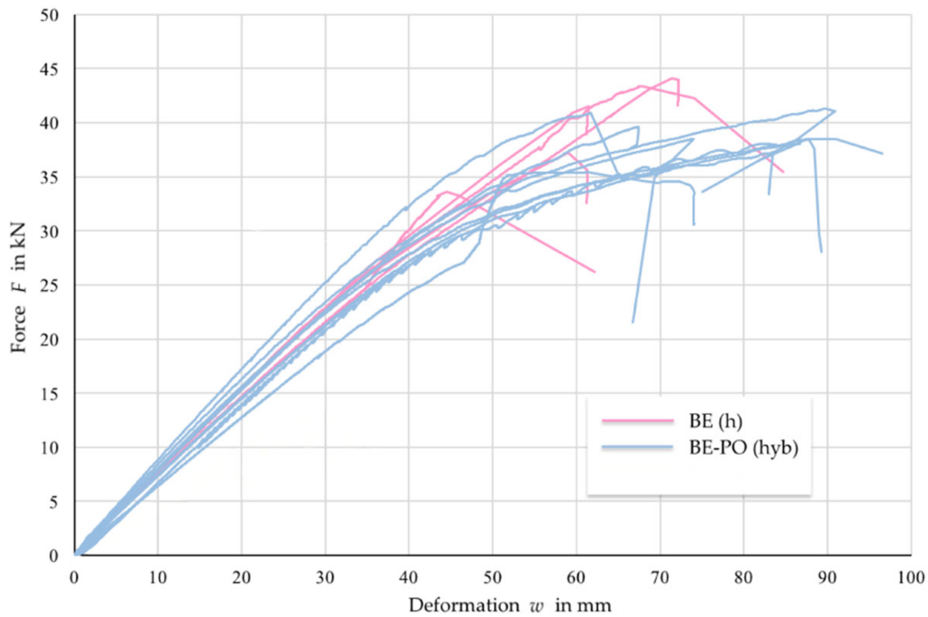

Figure 7. Graph of the F–w relationship for the glue-laminated beams; BE (h) stands for beech homogeneous glue-laminated beams and BE-PO (hyb) stands for beech–poplar hybrid glue-laminated beams.

The average maximum force for homogeneous beech beams (BE (h)) was reached at 39.98 kN (SD = ±3.99 kN), and for the hybrid beech–poplar (BE-PO (hyb)), this was reached at 38.68 kN (SD = ±1.78 kN). A higher deformation was found for the hybrid beams: 75.9 mm on average. The deformation of homogeneous beech beams was 60.1 mm on average. The values of bending strength are given in Section 3.2.

The first visible failure (crack propagation) was observed in the tensile zone of the homogeneous beech beams; this failure was followed by partial inter-layer delamination in some specimens (Figure 8).

Figure 8. Examples of failure of the homogeneous beech beam (BE (h)) (authors' archive).

For most of the hybrid beech–poplar beam specimens, the first visible failure (crack propagation) was observed in the tensile zone. However, in some specimens, there were failures of poplar lamellae in the inner zone, while the beech lamellae stayed intact in the tensile zone. Failure of the poplar lamellae in these specimens often occurred in the shear (Figure 9).

Figure 9. Examples of failure of the hybrid beech–poplar beam (BE-PO (hyb)) (authors' archive).

3.2. *Strength of the Glue-Laminated Beams in the Four-Point Bending Test*

Based on the results of the performed tests, the average bending strength of the homogeneous beech beams (BE (h)) was 89.1 N/mm^2 and the average bending strength of the hybrid beech–poplar beams (BE-PO (hyb)) was 83.0 N/mm^2. The obtained bending strength in the four-point bending test is shown in the graph in Figure 10.

The final values of the bending strength are summarized in Table 1.

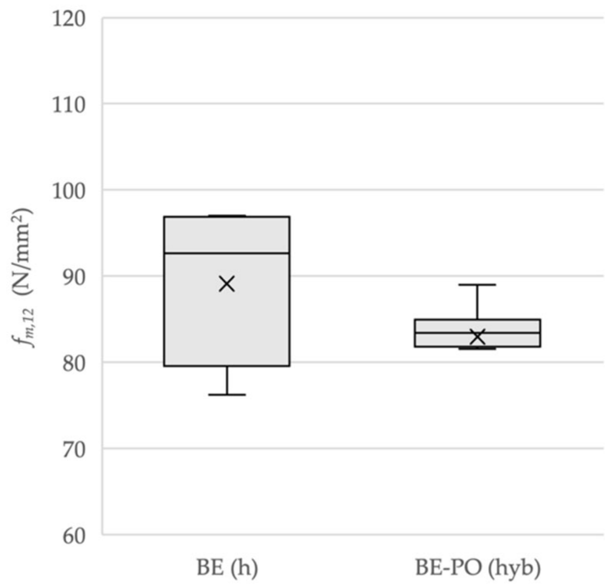

Figure 10. Experimental results expressed in a box plot.

Table 1. Bending strength of the glue-laminated beams.

$f_{m,12}$ v N/mm^2	BE (h)	BE-PO (hyb)
A $\bar{x}$	89.1	83.0
Median $\tilde{x}$	92.7	83.4
Standard deviation (SD)	8.2	3.85
Coefficient of variation (CV)	9.2%	4.6%

The experimentally measured bending strength of the beech homogeneous beams is comparable to the bending strength of the hybrid beech–poplar beams. For the statistical evaluation, see Section 3.4.

Based on the results of the individual lamellae tests, the average bending strength of the beech lamellae was 113.4 N/mm^2, for the poplar lamellae, it was 62.9 N/mm^2, and for the spruce lamellae, it was 63.3 N/mm^2. The final values of the measured bending strength are summarized in Table 2.

Table 2. Experimentally measured bending strength of the lamellae.

$f_{m,12}$ v N/mm^2	Beech	Poplar	Spruce
Average $\bar{x}$	113.4	63.6	63.3
Median $\tilde{x}$	115.4	63.4	63.5
Standard deviation (SD)	7.4	2.7	10.2
Coefficient of variation (CV)	6.5%	4.2%	16.4%

Based on the experimental results, beech wood shows an 80% higher bending strength than poplar; the bending strength of poplar is similar to that of spruce. For the statistical evaluation, see Section 3.4.

3.3. Modulus of Elasticity of the Glue-Laminated Beams in the Four-Point Bending Test

Based on the results of the performed tests, the average modulus of elasticity of the homogeneous beech beams was 22,439 N/mm^2, and the average modulus of elasticity of the hybrid beach–poplar beams was 22,254 N/mm^2. The test results of the modulus of elasticity of the glue-laminated beams in the four-point bending test are shown in the graph in Figure 11.

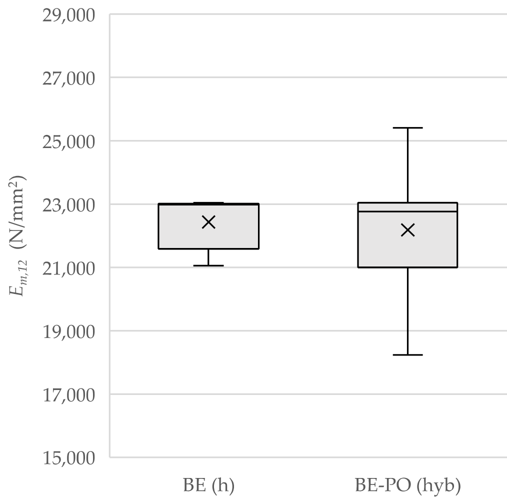

Figure 11. Test results of the modulus of elasticity of the glue-laminated beams in the four-point bending test displayed in a box plot.

The final values of the modulus of elasticity are summarized in Table 3.

Table 3. Modulus of elasticity of the glue-laminated beams.

$E_{m,l,12}$ v N/mm^2	BE (h)	BE-PO (hyb)
Average $\bar{x}$	22,439	22,185
Median $\tilde{x}$	22,982	22,773
Standard deviation (SD)	767	1859
Coefficient of variation (CV)	3.4%	8.4%

The experimentally measured modulus of elasticity of the beech homogeneous beams is very similar to the modulus of elasticity of the hybrid beech–poplar beams.

As for the results of the performed lamellae tests, the average modulus of elasticity for beech lamellae was 19,554 N/mm^2, the average modulus of elasticity for poplar lamellae was 12,780 N/mm^2, and the average modulus of elasticity for spruce lamellae was 16,504 N/mm^2. The test results for the modulus of elasticity of lamellae are shown in Table 4.

Table 4. Experimentally measured modulus of elasticity of the lamellae.

$E_{m,l,12}$ v N/mm^2	BE/Beech	PO/Poplar	NS/Spruce
Average $\bar{x}$	19,554	12,916	16,504
Median $\tilde{x}$	18,947	12,923	16,727
Standard deviation (SD)	1030	616	1921
Coefficient of variation (CV)	5.0%	4.8%	12.0%

Based on the experiment results, the beech wood shows a 53% higher modulus of elasticity than the poplar wood. The spruce lamellae behaved comparably to the beech lamellae in terms of the modulus of elasticity. For the statistical evaluation, see Section 3.4.

The beech GLT beams have a 15% higher modulus of elasticity than the individual lamellae of the same material (beech).

3.4. Statistical Analyses

The determined values of the bending strength and modulus of elasticity for the homogeneous beech and hybrid beech–poplar glue-laminated beams were evaluated with an unpaired two sample *t*-test under the assumption of equal variances with a significance level $\alpha = 0.05$.

Based on the Shapiro–Wilk test, neither the bending strength nor the modulus of elasticity distribution were statistically significantly different from the normal distribution. There is even no statistically significant difference between the variances either in the case of bending strength or in the case of the modulus of elasticity; this was verified using the Levene's test. The conditions for using the *t*-test were met in both cases. The results of the *t*-test are given in Table 5 (bending strength) and in Table 6 (modulus of elasticity).

Table 5. Unpaired two sample *t*-test results for the glue-laminated beams—bending strength.

$f_{m,12}$	Mean	Var.	*t* Stat	df	*p*-Value
BE (h)	89.11	84.57	1.76	12	0.104
BE-PO (hyb)	82.97	16.67			

Table 6. Two sample *t*-test results for the glue-laminated beams—modulus of elasticity.

$E_{m,l,12}$	Mean	Var.	*t* Stat	df	*p*-Value
BE (h)	22,439	735,831	0.27	12	0.79
BE-PO (hyb)	22,185	3,888,237			

For the bending strength, there were no statistically significant differences between the group mean values. This was determined by a *t*-test where the p-value > 0.05.

The results of the *t*-test for the modulus of elasticity show that there were no statistically significant differences between the group mean values as determined by the *t*-test performed (p-value > 0.05).

According to the statistical evaluation of the test results for beech, poplar, and spruce lamellae using the Shapiro–Wilk normality test, the distributions of beech, poplar, and spruce lamellae exhibit a normal distribution. The Levene's test results show that the variances are not equal. Based on these results, the Kruskal–Wallis test was used and showed a significant difference in the evaluated mean set values for both the bending strength and modulus of elasticity. The results of the Kruskal–Wallis test are given in Table 7.

Table 7. Kruskal–Wallis test results.

	Statistic	*p*-Value
Bending strength $f_{m,12}$	21.46	2.19×10^{-5}
Modulus of elasticity $E_{m,l,12}$	31.82	1.23×10^{-7}

A post hoc Dunn's test with a Holm's p-value adjustment was used to compare the results among the multiple pairwise comparisons (Table 8).

Table 8. Dunn's test results.

	Bending Strength $f_{m,12}$		Modulus of Elasticity $E_{m,l,12}$	
	p-value	Differences between the group mean values	*p*-value	Differences between the group mean values
Beech–poplar	1.2×10^{-4}	Statistically significant	5.9×10^{-7}	Statistically significant
Poplar–spruce	0.57	Statistically NOT significant	1.1×10^{-4}	Statistically significant
Spruce–beech	3.2×10^{-5}	Statistically significant	0.07	Statistically NOT significant

Using Dunn's test, it was found that there were no statistically significant differences between the mean values of the poplar and spruce bending strengths. In the case of the modulus of elasticity, it was found that there were no statistically significant differences between the spruce and beech mean values, while there were statistically significant differences between the mean values for spruce and poplar. Apart from the difference in the bending strength, the modulus of elasticity of poplar is not comparable to the modulus of elasticity of spruce.

3.5. Strength Class Grading

In order to classify the materials used into strength classes, the characteristic values of the lamellae of the different wood species would have to be determined. The classification is carried out according to the EN 384 standard [19] and requires a significantly higher number of lamellae to be tested. In order to estimate the approximate strength class of the tested bodies, the determination of the characteristic values according to EN 384 [19] for the lamellae and according to EN 14358 [41] for the beams was nevertheless carried out from the available number of samples. However, it must be pointed out that the values determined are not meaningful as they do not correspond to the conditions given by the standards.

The determined characteristic values and the appropriate classification into strength classes are shown in Table 9 for lamellae testing and Table 10 for GLT beam testing.

Table 9. Strength classes of the tested lamellae. Estimation of the strength classes according to EN 338 [18].

Samples	Property	Value	Class Corresponding to Value
Beech lamellae	ρ_k	574 kg/m^3	D40
	$f_{m,k}$	53 N/mm^2	D50
	$E_{0,\text{mean}}$	17,400 N/mm^2	D60
Poplar lamellae	ρ_k	311 kg/m^3	<D18
	$f_{m,k}$	29 N/mm^2	D27
	$E_{0,\text{mean}}$	11,800 N/mm^2	D30
Spruce lamellae	ρ_k	328 kg/m^3	C18
	$f_{m,k}$	24 N/mm^2	C24
	$E_{0,\text{mean}}$	15,250 N/mm^2	C45

Table 10. Strength classes of the tested GLT beams. Estimation of the strength classes according to [14,18].

Samples	Property	Value	Class Corresponding to Value
BE (h)	ρ_k	566 kg/m^3	D40
	$f_{m,k}$	46 N/mm^2	D45 >GL44c
	$E_{0,\text{mean}}$	20,750 N/mm^2	D70 >GL48c
BE-PO (hyb)	ρ_k	486 kg/m^3	D24
	$f_{m,k}$	49 N/mm^2	D45 >GL48hyb
	$E_{0,\text{mean}}$	20,500 N/mm^2	D70 >GL48hyb

4. Discussion

The results of the tests of glue-laminated beams show that it is possible to successfully combine different types of hardwood in a single GLT element. The homogeneous and hybrid beams showed high-strength characteristics. The beech lamellae had an 80% higher bending strength than the poplar lamellae. However, the use of poplar lamellae in the inner zone of the beam has apparently no effect on the bending strength and modulus of elasticity of the GLT beam. Both monitored values were comparable for both types of GLT beams (homogeneous and hybrid). Based on the experimental results, the density of hybrid beech–poplar beams in comparison to homogeneous beech GLT beams was approx. one-fifth smaller.

As shown in Figure 7, the course of the F–w relationship for homogeneous and hybrid elements was very similar up to the value of half of F_{max}. The difference occurred after further loading, beyond the value of half F_{max} when the hybrid GLT beams showed higher deformation than the homogeneous GLT beams.

According to the experimental test results (Table 1) and the statistical analysis (Table 5), it can be stated that there is no decrease in the bending strength of the hybrid beech-poplar beams compared to the homogeneous beech beams. The failure of the homogeneous GLT beech beams was (after initial pressure from the supports in compression perpendicular to the grain, which is common for bending tests) observed especially in the tensile zone, while the failure of the hybrid GLT beech-poplar samples was more often observed in the shear, as shown in Figure 9. From the point of view of the bending strength of the GLT samples, the behavior of most hybrid beams was affected by the shear failure of the poplar zone, while the behavior of homogeneous GLT beech beams was in all cases affected by the tensile failure of the tensile beech zones. In addition, the variability in the bending strength of the lamellae was lower for poplar than for beech, while the variability in the modulus of elasticity as comparable for both the beech and poplar lamellae. The lower variability in the results for the poplar lamellae is reflected in the variability of the results of the GLT beams.

It can be assumed that the lower variability in the bending strength of the hybrid beams is due to the influence of the lower variability in the poplar shear strength. A relatively small number of samples affected the variability of the results of the GLT beams to a certain extent. However, the obtained values from the tested samples can be, in general terms, considered low values of variability. From the point of view of the results, low variability in the hybrid beams is very beneficial.

The beech homogeneous GLT beams had a 22% lower bending strength in comparison to the tested beech lamellae (Table 2). This difference may be caused by the fact that the lamellae tests were performed with samples without knots and other imperfections (i.e., with ideal bodies), the compactness of the glued joints, or differences in the testing bodies' dimensions (the GLT cross-section is six times higher than the cross-sections of the lamellae). According to [42,43], the strength of the elements decreases with the growing dimensions (the so-called size effect).

From the point of view of the modulus of elasticity, the results of the experimental tests (Table 3) and the statistical analysis (Table 6) show that there was no decrease in the modulus of elasticity of the hybrid beech–poplar beams compared to the homogeneous beech GLT beams. It can therefore be concluded that the low modulus of elasticity of poplar is barely reflected in the modulus of elasticity of the entire hybrid GLT beam. Most of the load is carried by the outer beech lamellae (the strongest member).

The beams showed high values of strength characteristics, but due to the small number of samples, they could not be classified into strength classes with certainty. The strength classes and appropriate characteristic properties for the glue-laminated timber are defined in EN 14080 [11], which lists the values for homogeneous softwood. The values for hybrid glulam beams are listed in a regulation [14]. In addition, the classification according to the characteristic values found could not be completed accurately because the standards [11,14] state the maximum class GL32h and GL48hyb, respectively. However, the determined values of the tested glue-laminated beams were significantly higher than the specifications for these classes in the standards [11,14].

The works of Blaß and Frese [22], Muraleedharan and Reiterer [8], and Sciomenta et al. [23] used different types of wood. Primarily, the aim was to analyze the behavior of hybrid beams combining wood with a lower bending strength and wood with a higher bending strength. In all cases, the hybrid beams were compared to homogeneous beams comprised a lamellae wood type with higher bending strength. These results showed a lower bending strength for the hybrid elements in comparison to the homogeneous elements. In some cases, a comparison of the behavior of the hybrid beams to the behavior of the homogenous beams comprised the lamellae wood type with a lower bending strength was carried out. The results of the previously mentioned works showed that a decrease in the load-bearing capacity was present, independent of the type of wood and the cross-section dimensions used.

The reduction in the strength depends on the percentage of weight reduction and the type of wood used. The best weight decrease to strength reduction ratio was recorded by Blaß and Frese [22], where a 60% replacement of beech wood by spruce wood (from the cross-section area) meant just a 3% reduction of its bearing capacity, and a 67% replacement meant a 5% reduction of the beam bearing capacity. Regarding the replacement of a pine element with 67% poplar wood, Timbolmas [31] found a 14% reduction of the bearing capacity of the GLT element. Sciomenta et al. [23] reduced the weight of a beech element by replacing 50% of the lamellae with pine lamellae and recorded a 7% lower bending strength.

In contrast to the above-mentioned studies, in our research, only 33% of the beech lamellae were replaced and a 16% weight reduction was achieved. It was observed that the achieved weight reduction had no statistically significant effect on the bending strength and the modulus of elasticity of the GLT elements. It can be stated that the percentage of lamellae replacement was relatively low compared to the lamellae replacement of the GLT elements in the above-mentioned studies. It is clear that the lower the percentage of lamellae replacement, the lower its effect on the mechanical properties of the GLT element.

It is not possible to perform a comparison with the findings of study [8] since the mentioned study compares oak–spruce hybrid GLT beams with homogeneous spruce beams. In our research, a comparison of hybrid beech–poplar beams with homogeneous poplar beams was not carried out.

A glued element from a combination of several wood species can be functional. As stated above, it is possible to combine beech and poplar wood in one element; PUR adhesive can be used for gluing homogenous beech and hybrid beech–poplar elements. When using poplar wood, which has a comparable bending strength and a lower modulus of elasticity than spruce, 33% lamellae replacement in the inner zone had no effect on the bearing capacity of the member. This proves that the initial assumptions were correct.

5. Conclusions

This paper describes the results based on experimental tests performed on homogenous beech and hybrid beech–poplar glue-laminated beams made from local wood and glued with PUR adhesive.

Based on the results of this work, it is possible to conclude that:

(a) Both of the tested homogenous beech (BE (h)) and hybrid beech–poplar (BE-PO (hyb)) beams showed high values of strength characteristics. The characteristic values were determined according to the standard [19] although the number of tested elements was lower than the standard requires. The determined characteristic values for the hybrid GLT beams were even higher than those specified by standard [14] for class GL48hyb;
(b) The tested hybrid beech–poplar beams (BE-PO (hyb)) were approx. 16% lighter than the homogeneous beech beams (BE (h));
(c) The bending strength of the tested hybrid beech–poplar beams (BE-PO (hyb)) was comparable to the bending strength of the homogeneous beech beams (BE (h));
(d) The modulus of elasticity of the tested hybrid beech–poplar beams (BE-PO (hyb)) was comparable to the modulus of elasticity of the homogeneous beech beams (BE (h));
(e) Upon reaching approx. half of the maximum load, the homogeneous (BE (h)) and the hybrid (BE-PO (hyb)) beams behaved very similarly.

In the future, this research is to be extended to other aspects; particularly, it is necessary to examine:

- The possibility of increasing the percentage of beam weight reduction;
- The effect of lamellae layup on the bending strength of GLT beams;
- The cohesion of glued joints, particularly the beech–poplar joint;
- The effect of moisture fluctuation on the bond line.

Based on the obtained data, the current timber elements can be very successfully replaced with hardwood glulam elements. The production of glued beams from wood species other than the hitherto used wood species offers new possibilities for their use. Based on the higher load-bearing capacity of hardwood glulam elements, the cross-section depth can be reduced compared to spruce GLT beams. The reduction in the cross-section depth could be suitable for building renovations. In addition, in architectural and structural applications, beams with greater span to cross-section depth ratios are preferred by designers since they provide more open space with fewer obstacles.

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