

Article

Bonding Performance of Melamine–Urea–Formaldehyde and Polyurethane Adhesives for Laminated Hybrid Beams and Their Selected Mechanical Properties

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Abstract: Beech (*Fagus Sylvatica* L.) is a prevalent tree species in Slovenia and is suitable for manufacturing glulam beams. However, beech wood has certain limitations that can potentially be mitigated by combining it with Norway spruce (*Picea abies* (L.) Karst.) wood to create hybrid beams. This study aimed to determine the bonding performance of commonly used melamine–urea–formaldehyde and polyurethane adhesives for these hybrid beams. Moreover, how varying the proportion of beech wood in a hybrid beam affects its mechanical properties was examined. Shear and delamination tests (method B) were conducted, and EN 14080:2013 requirements were met in all cases. The four-point bending tests of the beams showed that hybrid beams containing 20% of beech wood in the cross-sectional height on each side of the neutral axis exhibited a similar modulus of elasticity values as pure beech beams, but their strength was not equally improved. Hybrid beams with 11% of beech wood did not show any improvement in bending stiffness or strength compared to pure spruce beams. It was noted that the presence of beech wood in a hybrid beam can influence its failure mode. Furthermore, analytical calculations showed that a symmetrical lay-up is preferable to an asymmetrical one to increase the effective modulus of elasticity.

Keywords: hardwood; glued laminated timber (glulam); construction adhesive bonding; mechanical characterization; MUF; PUR



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1. Introduction

Wood has become an increasingly interesting alternative to steel and concrete in recent years due to increased environmental awareness and the overall trend of sustainable construction. In Europe, softwoods are mainly used for construction purposes [1]. Due to climate change and the planned reduction in the share of spruce (*Picea abies* (L.) Karst.), the composition of Slovenian forests is changing and inclining towards a greater share of deciduous trees. The currently dominant tree species is European beech (*Fagus Sylvatica* L.), which represents 33% of all wood stock, followed by Norway spruce (*Picea abies* (L.) Karst.) at 30% [2]. The lack of standardization in terms of the production process, quality control, and structural design restricts the use of hardwood for construction [3]. Beech wood has a higher strength and stiffness than available softwoods, but it is also more expensive, has lower dimensional stability and lower biological durability, and it requires more demanding mechanical processing and drying. Some of the less advantageous properties of beech wood can be partly reduced by processing it into laminated veneer lumber (LVL) [4], but this requires a unique technological process. Combining beech wood with softwood could take advantage of both species and reduce the effects of defects, such as by gluing multiple lamellae from each wood. With beams assembled in this manner, hereinafter referred to as

hybrid beams, it would be possible to stimulate the utilization of beech wood and expand the possibilities of timber use in construction.

Adhesive bonding has been used in the production of structural members from wood for a long time. Gluing smaller lamellas into a larger entity improves dimensional stability, and the yield of raw material increases. Compared to solid wood, glulam beams with the same cross-section are usually not stronger; but the variability in strength is lower [5]. Melamine–urea–formaldehyde (MUF) and polyurethane (PUR) adhesives are the most common in the production of glulam beams. The main difference between these two adhesives is the elasticity and ductility of the glue bonds. Formaldehyde-based adhesives are usually brittle, while polyurethane adhesives can be formulated from very low-modulus adhesives to very hard and brittle systems. For wood bonding, the modulus of the elasticity of wood and adhesive should be the same. In this way, higher fracture strength can be reached since the peak stresses are not only absorbed by the wood but also by the bondline [6].

Most adhesive systems for structural bonding are designed for wood from conifers, and this can lead to non-suitable joints when gluing hardwoods. Most problems occur in delamination tests due to the high modulus of elasticity of wood and unfavourable shrinking and swelling [7]. The anatomical structure of beech wood can lead to starved bond lines if the viscosity of the adhesive is not adjusted correctly [8]. More extensive research on the structural gluing of beech wood was carried out by Schmidt et al. [9]. Based on their results and a related study by Blaß and Frese [10], a German national technical approval for the production of hybrid and glulam beams was issued [11]. For the quality control of adhesive joints, the technical approval prescribes the delamination test according to procedure C in EN 14080:2013 [12] and limits the use of beams to the first-use class in DIN EN 1995-1-1:2010 [13].

Blaß and Frese [10] studied the strength classification of hybrid glulam beams made of beech and spruce wood using experiments and theoretical considerations. Their study found that hybrid beams with a 20% share of beech wood in the cross-sectional height on each side of the neutral axis could be placed in the same strength class as beams made only of beech. Their conclusions only hold true if the outer beech lamellas in a hybrid beam possess slightly a higher bending strength of finger joints. These results are reflected in the German national technical approval [11], which categorizes beech and hybrid beams in strength classes up to GL48c/hyb.

EN 14080:2013 [12] does not contain any regulations for hardwoods (except poplar), primarily due to a lack of reliable data concerning material properties and methods for gluing and quality control. Since there are no standardized values for the tensile and bending strength of lamellas and finger joints of hardwoods, a reliable assessment of the load-bearing capacity of a glulam beam is difficult. In addition, a suitable shear and delamination test for the quality control of the glue line has not yet been developed [14]. It needs to be considered that the higher strengths are achieved only in the case of beech wood, which is visually or machine-graded into higher strength classes. The machine grading of beech wood is currently rarely used in industry. Additionally, the machining and gluing processes for such beams are different, and this presents a challenge with regard to integration into the existing production processes of companies producing glulam beams from softwoods. The use of solid beech wood for construction purposes is therefore limited to small market niches in the first-use class [4]. To encourage the use of hardwoods for such purposes, the current standards applicable for softwoods must be supplemented with new requirements for hardwoods [15]. The European Committee for Standardization (CEN-TC124/WG3/TG1) has established a working group to prepare a standard draft that will regulate the production and mechanical characterization of glued laminated timber made of hardwoods [16].

A research study on the mechanical characterization of hybrid glulam beams, combining beech and Corsican pine, was conducted by Sciomenta et al. [17]. The hybrid beams were compared to homogenous beech beams, all having a cross-section of $120 \times 144 \text{ mm}^2$

and consisting of eight 18 mm thick lamellas bonded with melamine-based adhesives. The beech wood in the hybrid beams accounted for 25% of the cross-sectional height at the top and bottom. The results indicated that both beam types exhibited similar mechanical performance, although the homogenous beech beams showed 8.3% higher bending strength than the hybrid ones.

In another study conducted by Šuhajdová et al. [18], hybrid beams were produced by combining beech and poplar wood. The hybrid beams comprised 33.3% of beech wood in the cross-sectional height on both sides of the neutral axis. All beams contained six 20 mm thick lamellas and had a cross-section of $60 \times 120 \text{ mm}^2$, bonded with polyurethane adhesive. The study found that the hybrid beams exhibited comparable bending stiffness and strength to homogenous beech wood beams while being approximately 16% lighter.

While previous studies primarily focused on the mechanical performance of hybrid beams [10,17,18] or the bonding performance of only one single wood species [7,9,15,19–21], this study combined beech and spruce wood to a hybrid beam to assess its bonding performance. Emphasis was placed on investigating the effect of moisture fluctuation on the bond line and stress transfer between beech and spruce wood. Furthermore, the research aims to investigate the mechanical properties, even if the ratio of beech wood in the hybrid beam is decreased.

The goals of this study are to carry out the following:

- (i) Determine the bonding performance of commonly used PUR and MUF adhesives in the production of softwood glulam when applied to laminated hybrid beams made of spruce and beech;
- (ii) Study how the relative share of beech wood in a hybrid glulam beam affects its stiffness and strength.

For (i), shear and delamination tests were performed on small beam samples, and for (ii), four-point bending tests were performed on assembled hybrid beams, supplemented with analytical calculations of the effective modulus of elasticity (MoE). The results indicate that both used adhesives met the requirements of the mentioned tests. Hybrid beams with 20% beech wood on each side of the neutral axis had a similar modulus of elasticity as pure beech beams but did not show the same improvement in strength. The symmetrical composition is more favourable for an effective modulus of elasticity than the unsymmetrical one.

2. Materials and Methods

2.1. Shear and Delamination Test

Two small beams with outer dimensions of $105 \times 100 \times 520 \text{ mm}^3$ using five 20 mm thick lamellas were made to test the adhesives. The outer two lamellas were from beech wood (*Fagus Sylvatica* L.), and the inner three were from spruce wood (*Picea abies* (L.) Karst). For beam 1, a MUF adhesive DYNEA PREFERE 4535 with hardener 5046 was used. The adhesive was prepared with a mass ratio of 100 parts of resin to 30 parts of hardener. PREFERE 4535 meets the requirements of EN 301:2013 [22] Type 1 and is classified as a general-purpose and finger-jointing adhesive suitable for both mixed and separate application. It can effectively bond various softwoods and hardwoods, such as birch and beech. The resin contains a solid content of 63–65%, a pH value at 25 °C ranging from 8.5 to 10, and a viscosity of 3000–6000 mPa·s at 25 °C. The hardener used, PREFERE 5046, has a pH of 0.7–1.3 at 25 °C and a viscosity of 2500–5000 mPa·s at 25 °C (the viscosities of resin and hardener are measured using Brookfield, RVT, spindle 4 at 20 rpm) [23]. For beam 2, LOCTITE HB S109 PURBOND with primer PURBOND PR 3105 was used. It is a liquid single-component polyurethane adhesive (PUR) with 100% solid content. The adhesive cures in the reaction with air humidity and wood moisture, forming a non-brittle bond. The minimal required moisture content of wood is 8%. The adhesive has a viscosity of 24,000 mPa·s at 20 °C (measured by Brookfield, spindle 6 at 20 rpm) and is certified as Type 1 according to EN 15425:2017 [24,25]. The PUR adhesive manufacturer prescribes a primer when gluing beech wood, so a primer was applied in two of the glue bonds while the other

two were without it. The primer concentrate was mixed with water to a 10% solution (based on weight percent). Both adhesives were applied using a spatula on only one adherend, while the primer was applied to both sides using a sponge. The used spruce and beech wood was free of knots, red heartwood, or other anomalies. The average moisture content of spruce and beech wood was 10% and 8.1%, respectively, and this is determined using cut-offs via the gravimetric method (EN 13183-1:2002 [17]). The gluing parameters are shown in Table 1. After gluing, the shear and delamination test specimens were cut and conditioned in standard climate ($T = 20\text{ }^{\circ}\text{C}$, $\text{RH} = 65\%$) for two weeks, according to EN 14080:2013 [12]. For each adhesive, the tests comprised six specimens for the shear test and three specimens for the delamination test (procedure B), as shown in Figure 1.

Table 1. Gluing parameters of smaller beams.

Beam	Adhesive	Adhesive Application	Open Assembly Time	Closed Assembly Time	Specific Clamping Pressure	Primer Application	Primer Activation Time	Pressing Time	Curing Temperature
		(g/m^2)	(min)	(min)	(MPa)	(g/m^2)	(min)	(h)	($^{\circ}\text{C}$)
Beam 1	MUF	400	0	25	1	/	/	19	23
Beam 2	PUR	150	0	9	1	20	25	19	23

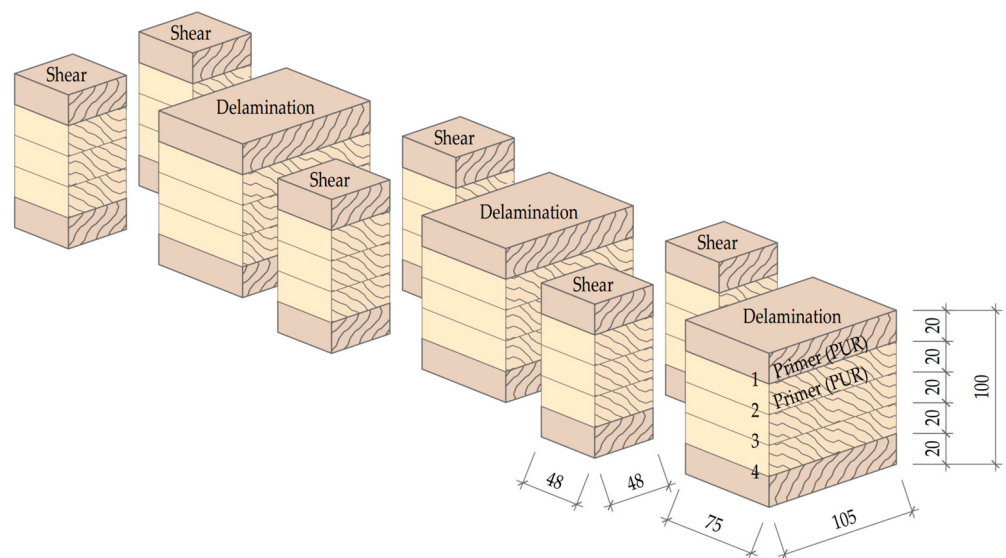


Figure 1. Samples for the delamination and shear test (dimensions in mm).

2.2. Four-Point Bending Test

To determine how the share of beech wood in a hybrid beam affects its bending stiffness and strength, four-point bending tests according to EN 408:2010 [26] were performed. Four types of beams were tested, as specified in Figure 2, using two samples of each type. The first and second types were references made of only spruce and only beech, respectively. The third (Hybrid 20-20) and fourth types (Hybrid 11-11) were hybrid beams with the outer lamellas made of beech wood and the inner from spruce wood. The share of beech wood on each side of the neutral axis for the third and fourth group was 20% and 11%, respectively. The selection of a 20% beech wood share was based on its alignment with the specified amount in the German national technical approval for hybrid glulam beams [11]. Another preliminary study, which utilized the finite element method, investigated the optimal share of beech wood in a hybrid beam to achieve the highest specific bending strength. The determined amount was 11% of the cross-section height on each side of the beam; however, the model ultimately proved to be inadequate and is therefore not presented in this paper. The beams had a cross-section of $100 \times 100\text{ mm}^2$ and were 1630 mm long. Each beam

was composed of five lamellas free of anomalies and finger joints. The dynamic modulus of elasticity of the lamellas was determined with the vibration resonance method, using transverse and longitudinal excitement, as presented in Straže et al. [27]. For the execution of this method, the density of the material (ρ) must be known, and this was determined by weighing the lamellas (m), measuring them in all dimensions (to determine the volume V), and calculating it using the equation $\rho = m/V$. The average values of the density and dynamic moduli of elasticity of used lamellas are shown in Table 2.

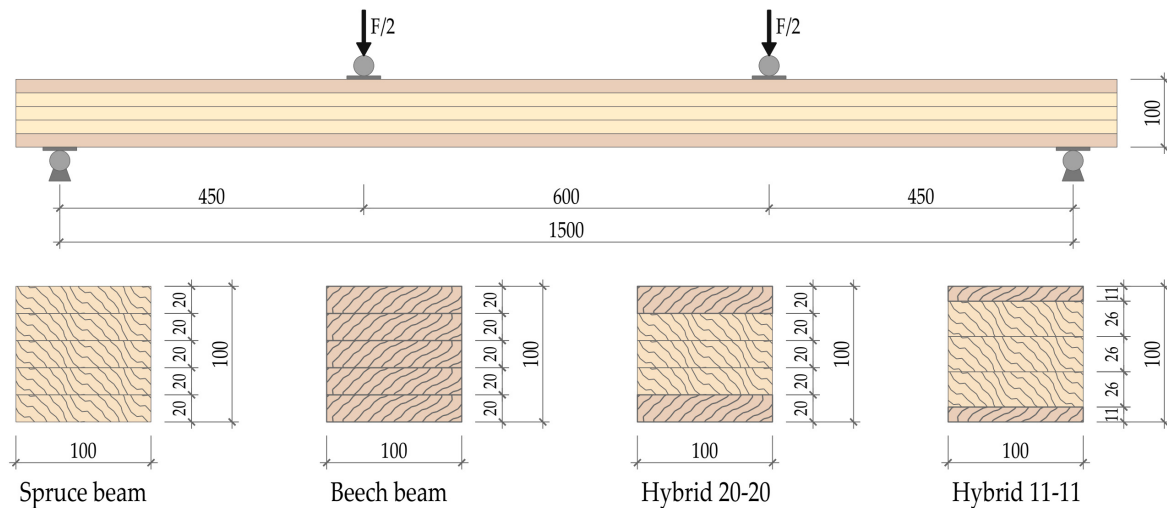


Figure 2. Setup of the four-point bending test and all groups of tested beams (dimensions in mm).

Table 2. Average values of the density and dynamic moduli of elasticity (longitudinal and transverse excitement) of lamellas used in the beams for the four-point bending tests.

	Average Density (kg/m ³)	Average Dynamic MoE (Longitudinal) (GPa)	Average Dynamic MoE (Transverse) (GPa)	Number of Lamellas
Beech	741	18.6	18.3	18
Stand. Dev.	30	1.0	1.1	
CoV	4.0%	5.6%	5.9%	
Spruce	482	16.4	15.9	22
Stand. Dev.	27	0.9	1.0	
CoV	5.7%	5.4%	6.1%	

To ensure an active surface, the lamellas were planed just before gluing. MUF adhesive DYNEA PREFERE 4546 in combination with 5020 hardener was used, prepared in the same manner as described above. This adhesive was used because the DYNEA PREFERE 4535 used for shear and delamination tests was currently unavailable at the local supplier. The adhesive systems are similar, although DYNEA PREFERE 4546 differs by having gap-filling properties and the ability to be used at lower pressing pressure in special cases. However, it is not permitted to bond beech glulam [28]. The beams were assembled in a manner such that the outer lamellas had a higher modulus of elasticity than the inner ones. In the four-point bending test, the global modulus of elasticity was determined. Displacement was measured at the points of load application and not at the middle of a beam, as described in the related standard; therefore, the global modulus of elasticity was calculated using Equation (1). The equation is based on Timoshenko's beam theory and can be used to calculate the global modulus of elasticity when the displacement at load-applying points is known [29]. Since Timoshenko's theory is shear-flexible, it also accounts for deformations caused by shear, which cannot be neglected in the chosen setup. The value of the shear modulus was set and assumed as 1/16 and 1/10.3 of the modulus of elasticity for spruce wood and beech wood, respectively, which was adopted from DIN 68364:2003 [30]. For

the hybrid beams, the corresponding ratio was assumed the same as for spruce wood, considering that the highest shear stresses occur at the neutral axis. In the calculation, the displacement values at 10% and 40% of the ultimate force were used.

$$E_{\text{glob.}} = \frac{FA^2B}{4wI} + \frac{FA^3}{6wI} + \frac{Fk_sA}{2wbhG_R} \quad (1)$$

Here, $E_{\text{glob.}}$ is the global modulus of elasticity, MPa; A is the distance between the load-applying point and closest support, mm; B is the distance between load applying points, mm; b is the width of a beam, mm; h is the height of a beam, mm; G_R is the ratio between the shear and elastic modulus of elasticity; F is the increment of load ($0.4 F_{\text{max}} - 0.1 F_{\text{max}}$), N; w is the increment of displacement relating to load F , mm; k_s is the coefficient -1.2 for rectangular cross-sections; I is the moment of inertia of a beam, mm^4 .

Bending strength was calculated according to Equation (2) (EN 408:2010 [26]):

$$f_m = \frac{3F_uA}{bh^2} \quad (2)$$

where f_m is the bending strength, MPa, and F_u is the ultimate load, N.

2.3. Analytical Calculation of the Effective Modulus of Elasticity

The influence of outer beech lamellas on the bending stiffness was also calculated analytically. The effective modulus of elasticity was calculated for three different compositions of a beam: (i) symmetrical composition (equal proportion of beech wood on the top and bottom), (ii) beech wood only on the top side (compression zone), and (iii) beech wood only on the bottom side (tensile zone). The calculation was based on composite theory and employed the transformed section method [31], where the transformation factor was calculated according to Equation (3):

$$n = \frac{E_b}{E_s} \quad (3)$$

where n is the transformation factor, E_b is the modulus of elasticity of beech wood, MPa, and E_s is the modulus of elasticity of spruce wood, MPa.

As illustrated in Figure 3, the cross-section of the hybrid beam is converted into an equivalent shape made of only one wood type and consequently resembles I- or T-beams. The width of each wood species in the equivalent beam section changes depending on the transformation factor, whereas the height remains unchanged. The modulus of elasticity of a transformed hybrid beam was calculated according to Equation (4). For the calculation, the glue lines were assumed to be rigid and infinitely thin, and the wood was assumed to behave as a homogeneous material with the modulus of elasticity not varying along the beam's length. The moduli of elasticity for spruce and beech wood used in the calculation were the average values of the moduli obtained from the four-point bending tests:

$$E_h = \frac{E_b I_b}{I_h} \quad (4)$$

where E_h is the modulus of elasticity of a transformed hybrid beam, MPa; E_b is the modulus of elasticity of a beech beam, MPa; I_b is the moment of inertia of a beech beam, mm^4 ; I_h is the moment of inertia of a hybrid beam, mm^4 .

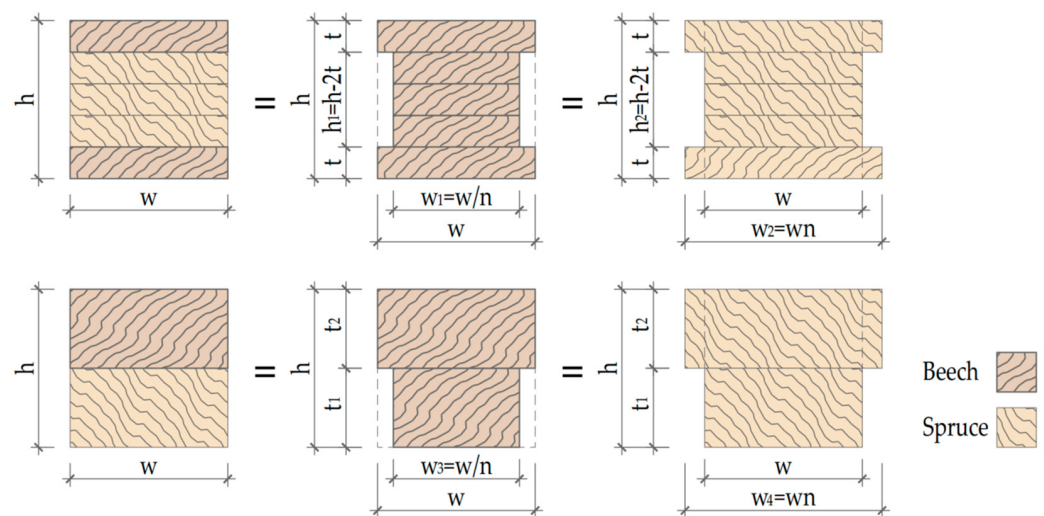


Figure 3. Transformation of beam cross-sections, which are made of lamellas with different moduli of elasticity according to the composite theory (n is the transformation factor).

3. Results and Discussion

3.1. Delamination Test

The requirements of the delamination test (method B) according to EN 14080:2013 [12] were met in all bonding cases. Figure 4 shows the samples after testing, revealing no delamination between glue lines. Also, the bonds between beech and spruce wood turned out to be unproblematic. The adhesives used were of type I according to EN 301:2017 [22] (MUF) and EN 15425:2017 [24] (PUR), which applies to softwoods, making it difficult to interpret the results since the stresses at shrinkage are lower in softwoods than in beech wood. In the beam bonded with PUR adhesive, both beech lamellas were strictly and radially oriented; this enables the relevant comparison of the primer effect. Lamellas with radial orientations represent the most unfavourable condition in delamination tests. The glue line is affected by transverse tensile stresses caused by the tangential shrinkage, which, on average, is twice the radial one [32].

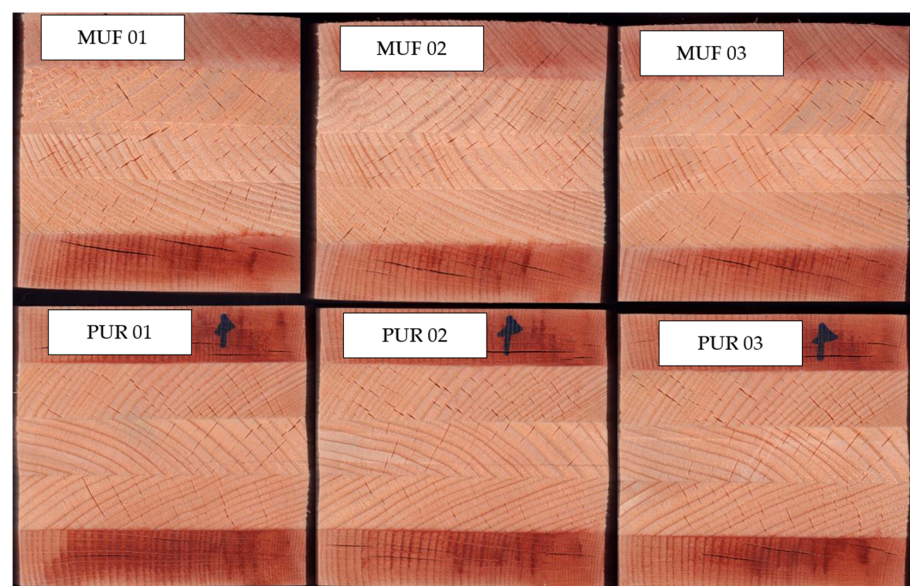


Figure 4. Samples after the delamination test.

No differences in the delamination were observed when using PUR adhesive alone and in combination with a primer. The used primer has proven to improve bonding

performance when gluing beech wood [15,33]. In this study, the potential benefits of the primer would have been more significant if the beams contained more beech lamellas, resulting in glue lines only between beech wood, which is more challenging to bond.

The results also indicated that the gluing parameters were adequate, particularly with regard to the gluing pressure and closed assembly times. According to Schmidt et al. [9], the delamination of beech wood glulam samples made of 30 mm thick lamellas showed a significant decrease when the closed assembly time was extended to 45–75 min. Similarly, Clerc et al. [19] found that in the case of one-component polyurethane adhesive, a prolonged closed assembly time had a positive impact on the delamination test's results, as it allowed the adhesive to penetrate further. However, in the presented study, the closed assembly times were 25 and 9 min for MUF and PUR, respectively, which are relatively low.

For the quality control of hybrid beams, the German national technical approval [11] prescribes the execution of the delamination test via method C, for which its requirements are less strict than those of method B, with the latter used in this study. The high performance of our samples is likely due to the small thickness and width of the lamellas, which generate lower shrinking stresses compared to thicker and wider ones. Other authors [9,15,19,20] also reported the positive impact of thinner lamellas on delamination when bonding hardwoods. The beech lamellas also did not contain any red heartwood, which can negatively impact delamination test results [34]. It needs to be mentioned that the adhesive systems used for shear and delamination tests are now certified for the production of hybrid beams according to the German national technical approval [11]. However, it should be noted that in the case of the polyurethane system, only LOCTITE HB S309 PURBOND with a closed assembly time of 30 min, in combination with a primer, is permitted, unlike the one used in this study with a closed assembly time of 10 min [35].

3.2. Shear Test

Table 3 shows the results of the shear test of samples glued with PUR and MUF adhesives. All glue lines in the tests met the requirements of EN 14080:2013 [12], which specifies a minimum average shear strength of 6 MPa with at least 90% wood failure. For all tested glue lines, 100% wood failure was observed. In glue lines between spruce and beech wood, failure occurred in both wood species. The position of the samples in the testing jaws played a vital role if the failure was initiated in beech or spruce wood. If the failure occurred in beech wood, then shear strengths were slightly higher than for failure in spruce wood, which is due to the higher shear strength of beech compared to spruce. Glue lines between spruce and beech have, on average, reached slightly higher strength values than glue lines between spruce only. The highest shear strengths were reached by PUR adhesives in combination with a primer, followed by MUF and PUR adhesives without a primer, but the differences were not significant. The mentioned standard applies to softwoods, leading to the question of what shear strength could be required for the bond between spruce and beech wood. Previous research by Aicher [21] found that the bonds of beech glulam can reach a mean shear strength of 18.9 MPa, which aligns with similar values reported by Luedtke [15]. Considering the chain-link model of adhesive bonds presented by Marra [36] in which the chain is only as strong as its weakest link, in the case of bulk spruce wood, the shear strength of spruce wood should be decisive.

3.3. Four-Point Bending Test

Figure 5 shows the values of bending strengths and the moduli of elasticity obtained from the four-point bending tests. It shows that the moduli of Hybrid 20-20 and pure beech beams differed little (at most 0.5 GPa). The explanation lies in the position of the beech lamellas, where the normal stresses occurring during bending are at their highest. However, a similar increase in bending stiffness compared to pure spruce beams cannot be observed for Hybrid 11-11 beams. The reason may lie in the lower modulus of elasticity of the used beech and spruce lamellas, as determined in the vibrational tests. In addition,

the moduli of elasticity of the pure spruce beams were exceptionally high compared to the values stated in EN 338 [37].

Table 3. Results of the shear tests of samples glued with PUR and MUF adhesives.

Glue Line (PUR)	Average Shear Strength f_v (MPa)	Stand. Dev. (MPa)	CoV	Number of Samples	Notes
1 (beech–spruce)	10.65	0.78	7.34%	6	Primer Primer
2 (spruce–spruce)	10.23	1.10	10.73%	6	
3 (spruce–spruce)	8.47	0.90	10.62%	6	
4 (spruce–beech)	9.58	1.30	13.61%	6	
Glue line (MUF)					
1 (beech–spruce)	9.85	1.00	10.18%	6	
2 (spruce–spruce)	9.71	1.20	12.37%	6	
3 (spruce–spruce)	8.95	0.80	8.89%	6	
4 (spruce–beech)	10.20	0.67	6.58%	6	

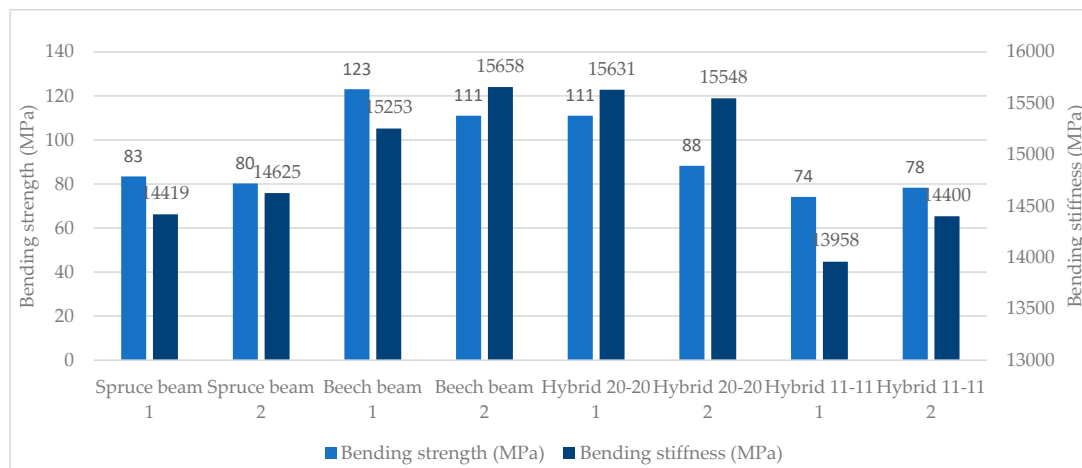


Figure 5. Values of bending strengths and moduli of elasticity obtained with four-point bending tests.

Equation (2) was based on a calculation of bending strength, in which the compression strength was the same or higher than the tensile strength. In this study, however, the lamellas were free from finger joints and other defects; therefore, the tensile strength was higher than the compression strength. At maximum load during bending, the neutral axis was no longer in the middle but moved to the tension side due to failure in compression. The stresses in the plastically deformed compression zone were lower than in the tension zone. This means that the calculation of the bending strength for beams that have exceeded the proportionality limit is no longer correct according to this equation. The calculated bending strength is thus not the actual maximum bending stress that occurs in a beam. Despite this limitation, the calculated bending strength has an essential role when comparing different composite materials with each other [38].

As expected, the highest bending strengths were achieved by beech beams, as shown in Figure 5. The bending strength of Hybrid 20-20 beams was approximately midway between that of beech beams and spruce beams. The strength of Hybrid 11-11 beams was practically indistinguishable from pure spruce beams. This, again, could be attributed to the used wood. All beech and spruce beams collapsed due to tensile failure after large plastic deformations in the compression zone, as shown in Figure 6a–d. Since only two samples were tested for each beam type, general observations are difficult. However, shear failures (Figure 6e–h) were observed to occur for hybrid beams if the outer beech lamella in the tension zone was overly strong. Of all hybrid beams, only Hybrid 20-20 2 exhibited bending failure; for all others, shear failure dominated. The cross-section of the tested beams was a square, which is more favourable for the distribution of longitudinal shear stresses than for rectangular cross-sections, where the affected surface by shear stresses is

relatively smaller. No delamination failure between beech and spruce wood lamellas was observed, indicating good bonding performance. The common occurrence of shear failure in hybrid glulam beams was also observed by Sciomenta [17] and Šuhajdová [18], where they combined beech wood with Corsican pine and beech wood with poplar, respectively. In these two studies and the one presented in this paper, the lamellas did not contain finger joints, which can represent a weak point, particularly in tension-loaded lamellas. However, in the study by Blaß and Frese [10], hybrid beams did contain finger joints, and they reported that the dominant failure mode was either caused by finger joints, knot failure, or a combination of both.



Figure 6. Beams after four-point bending tests. (a) Beam beech 2; (b) bending failure of beam beech 2; (c) beam spruce 2; (d) bending failure of beam spruce 2; (e) beam Hybrid 20-20 1; (f) shear failure of beam Hybrid 20-20 1; (g) beam Hybrid 11-11 2; (h) shear failure of beam Hybrid 11-11 2.

Figure 7 shows the load–displacement curves of all beams. It can be observed that hybrid beams with 11 mm thick lamellas failed in a more ductile manner, which is preferable to brittle collapse [39]. Considering that the shear failure in hybrid beams is common if the lamellas in the tension zone have high tensile strength, reinforcing the parts of the beam where shear stresses are most significant could be advantageous. This reinforcement could promote ductile failure and could be achieved using inclined, fully threaded screws.

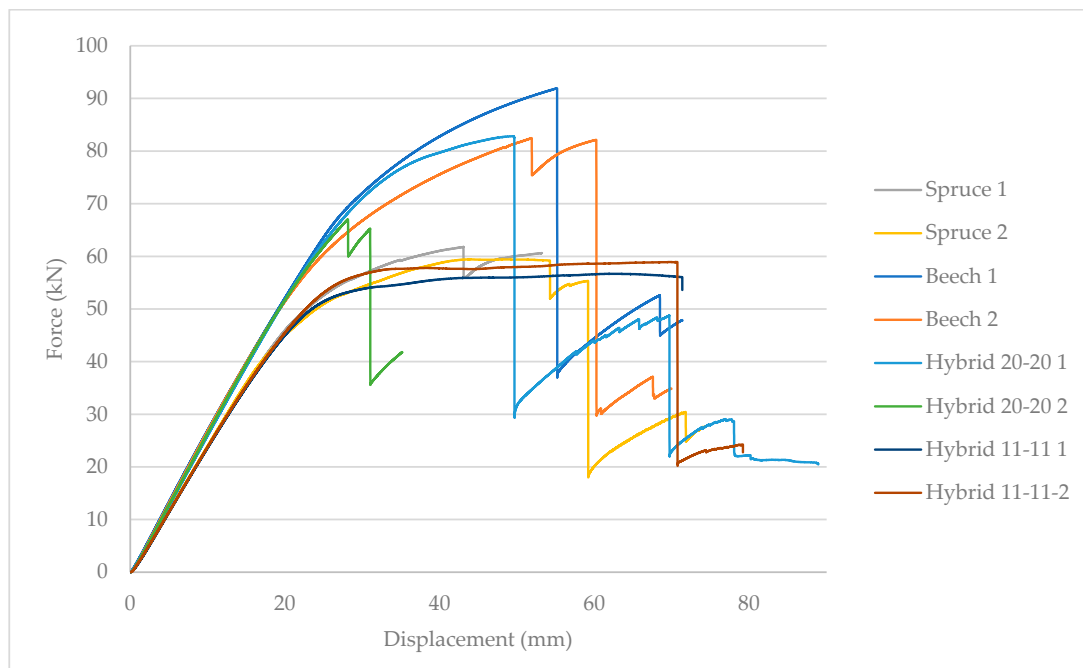


Figure 7. Load–displacement curves for all beams tested in four-point bending tests.

The average bending strength and bending stiffness of Hybrid 20-20 beams were higher than those of spruce beams by 22% and 7%, respectively. Compared to beech beams, the average bending strength of Hybrid 20-20 beams was 18% lower, while the bending stiffness remained nearly the same. Therefore, Blaß and Frese’s [10] findings can only be confirmed for bending stiffnesses and not for bending strength. It is important to note that their study included lamellas with knots and finger joints, which influence the bending strength, making the comparison less relevant. Among the four groups, Hybrid 11-11 beams performed the worst and did not exhibit any improvement compared to spruce beams, except for a more ductile failure mode.

3.4. Analytical Calculation of the Effective Modulus of Elasticity

Figure 8 shows how the effective modulus of elasticity changes by varying the share of beech wood in a beam. The solid curve corresponds to a symmetrical lay-up, where beech lamellas are placed at the top and bottom in a beam. The dashed curve corresponds to an asymmetrical lay-up, in which beech wood is placed on only one side of the neutral axis and where the share of beech is varied. The bottom left position in the figure represents a pure spruce beam, and the top right represents a pure beech beam. For an asymmetrical lay-up, the position of beech wood (whether bottom or top) does not affect the effective modulus of elasticity, although the position of the neutral axis varies. Nevertheless, the position of beech wood could have a major impact on bending strength due to differences in compression and tension strength. Comparing the curves in Figure 8, it is evident that the effective modulus of elasticity increases faster with respect to the proportion of beech wood for a symmetrical lay-up than for an asymmetrical lay-up. The reason for this is the higher moment of inertia of the cross-section of a symmetrical transformed beam. The moment of inertia is about 18% higher for a symmetrical lay-up with 20 mm thick beech lamellas than

for an asymmetrical lay-up with a single 40 mm thick lamella. This percentage is only valid for the specific ratio of the moduli of elasticity in this study, according to composite theory. The beam with the symmetrical lay-up performs similarly to an I-beam, where stiffness is allocated to the regions with the highest stresses.

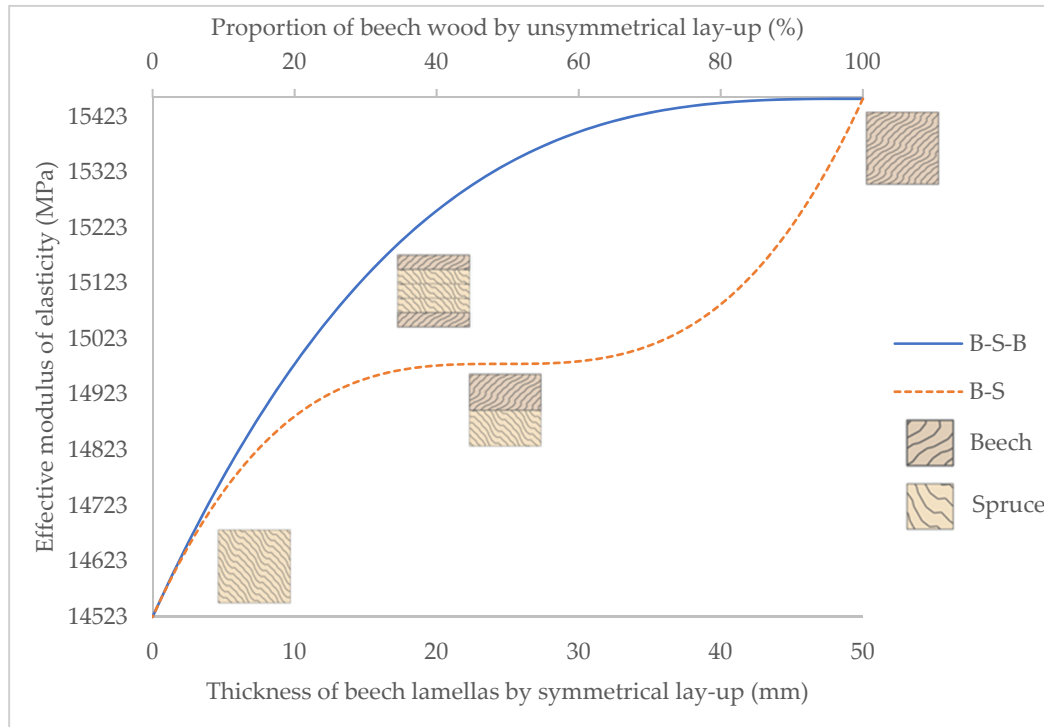


Figure 8. Effective modulus of elasticity as a function of the thickness of beech lamellas in a symmetrical (solid line) and asymmetrical (dashed line) lay-up.

4. Conclusions

In this study, the bonding performance of PUR and MUF adhesives for hybrid beams made of spruce and beech wood was assessed, and the influence of the relative share of beech on the stiffness and strength of these beams was investigated. Delamination tests, shear tests, four-point bending tests and analytical calculations for the effective bending stiffness of hybrid spruce-beech beams and pure spruce and beech beams were conducted. The results show the following:

- MUF and PUR adhesives, without or in combination with a primer, can meet the requirements of the shear and delamination test (method B) according to EN 14080:2013 [12];
- Hybrid beams of spruce and beech with 20% of the cross-section's height made of beech on each side of the neutral axis can reach similar modulus of elasticity values compared to pure beech beams and exhibit higher strength compared to pure spruce beams;
- Hybrid beams of spruce and beech with 11% of the cross-section's height made of beech on each side of the neutral axis differ little in terms of the modulus of elasticity and strength compared to pure spruce beams;
- The presence of beech in a hybrid beam can influence the failure mode, and shear failure is likely to occur;
- A symmetrical lay-up of beech lamellas in a hybrid beam is more favourable for an increased and effective modulus of elasticity than an asymmetrical one.

The results show that beech and spruce wood can be successfully bonded to a hybrid beam. The bond line between beech and spruce wood exhibits resistance to moisture changes and effectively transfers bending stresses. By having a sufficient amount of beech wood in a hybrid beam, it is possible to attain similar mechanical properties as those of

pure beech beams. Further research should be carried out on samples with thicker lamellas and larger cross-sections to verify the presented findings. Moreover, the spruce wood of low-strength classes should be tested to maximize the benefits of hybrid compositions.

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