Influence of False Heartwood of European Beech (*Fagus sylvatica* L.) on Tensile Shear Strength of Lap Joints

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The aim of this research was to investigate the effect of false heartwood of beech wood on the shear strength of glued joints for thermoplastic and reactoplastic adhesives for plywood production. The tensile shear strength of the lap joints was tested for four different types of adhesives according to EN 204 (2016) and EN 205 (2016). The results showed that for lap joints assembled with polyvinyl acetate, urea-formaldehyde, and phenol-formaldehyde adhesives, there was no significant difference in shear strength between beech sapwood and false heartwood. However, for joints bonded with polyurethane adhesive, the shear strength was lower for heartwood compared to the reference sapwood, particularly after exposure to water immersion.

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Keywords: Beech wood; False heartwood; Lap joints; Shear strength; Polyurethane adhesive; Phenol-formaldehyde; Urea-formaldehyde

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INTRODUCTION

Beech wood (*Fagus sylvatica* L.) is currently used primarily for the production of shaped moldings and plywood (Durrant *et al.* 2016). Although beech is an important European wood species in terms of use, its use in construction is less compared to spruce. At the same time, the supply of already widespread beech in European forests is growing, and in the future there is expected to be a shortage of spruce wood, which will have to be replaced, for example, with beech wood (Podrázský *et al.* 2014). This problem has been exacerbated by the dry years, when large-scale bark beetle calamities have occurred in spruce monocultures in Central Europe, leading both to large fluctuations in timber prices on the market (Toth *et al.* 2020) and, paradoxically, to a subsequent shortage of wood raw material in the following years. In the past, many studies and research have already appeared on the use of beech in the construction industry (Ohnesorge *et al.* 2010; Luedtke *et al.* 2015). A major and increasingly discussed disadvantage of beech wood is the frequent occurrence of false heartwood (also called red heartwood or false core). There are several theories about its origin, but it has still not been fully clarified (Wernsdörfer 2006; Sorz and Hietz 2008; Račko and Čunderlík 2010). In terms of mechanical properties, beech wood with and without false heartwood is not considerably different (Pöhler *et al.* 2006). However, it is less popular because of its unaesthetic nature (Hansmann *et al.* 2009;

Lieskovsky *et al.* 2009). Often, efforts are made to remove the false heartwood from visual products, which can be achieved, for example, by choosing the right cross-section pattern (Popovic *et al.* 2014). However, this leads to significant economic losses (Hapla *et al.* 2002). It is preferably used for non-visible applications, *e.g.*, it is glued into the inner layers of plywood or laminated wood (Aicher and Ohnesorge 2011).

Another option is to partially minimize color differences *via* physical steaming (Tolvaj *et al.* 2009) or using thermal treatment of wood (Shi *et al.* 2007; Kocaefe *et al.* 2008; Widmann *et al.* 2012). These treatments have a negative impact on the mechanical properties of wood and are not economically advantageous. Considering the economy and ecology of production, it is most advantageous to use wood with false heartwood without treatment, even though this wood is demonstrably more susceptible to attack by some fungi, as there is a lower content of protective phenolic substances (Schwartze and Baum 2000; Koch *et al.* 2003; Vek *et al.* 2013).

The issue of gluing beech wood is gaining in importance and generally has been found to be problematic (Aicher and Ohnesorge 2011) from many aspects, such as temperature (Šedivka *et al.* 2015), moisture (Bomba *et al.* 2014), surface roughness (Budhe *et al.* 2015), or the thickness of the glued joint (Davies *et al.* 2009). From the point of view of the use of false heartwood in plywood, as well as other applications, it is important to assess whether the substances of false heartwood or its structure have an effect on the strength of the glued joint and how it differs depending on the type of adhesives used.

Some research on this topic has already been done in the past, but no significant change in the strength of the glued joint was observed (Pöhler *et al.* 2006; Aicher and Reinhardt 2007; Aicher and Ohnesorge 2011a). A difference was only observed in the case of climate changes for isocyanate-based adhesives, *i.e.*, polyurethane adhesives (PUR), probably because of an unknown measurement error (Ohnesorge *et al.* 2006). Polyurethane adhesives, which are gradually replacing all other types of adhesives because of their formaldehyde-free formulation, are specific in that they harden *via* moisture absorption (Kristak *et al.* 2023). The presence of tyloses in the beech heartwood partially slows down the movement of free water in the wood during drying (Shahverdi *et al.* 2013). In practice, this can lead to different final moisture contents, which can potentially affect the final bond strength of some adhesives (Bomba *et al.* 2014). For wood with false heartwood, PUR adhesives might cure better because the wood contains more moisture. However, this assumption needs to be verified by further tests. The tests done by Ohnesorge *et al.* (2006) were conducted according to the standards for testing adhesives for construction purposes. However, no attention has been paid to the influence of false beech heartwood for adhesives for non-structural purposes.

It can be assumed that the other differences are due to the different chemical structure of wood with false heartwood. Unlike the coloring of beech wood during the steaming process, where condensation of simple phenolic substances takes place in the lumens of longitudinal cells (Koch *et al.* 2000, 2003), the formation of false heartwood is attributed to the oxidation of catechins (Hofmann *et al.* 2008; Sorz and Hietz 2008; Vek 2013) in locations where the tree is damaged (Račko and Čunderlík 2010). As a result, the total content of phenolic substances in false heartwood is probably lower than in sapwood (Vek 2013), which can also affect the glued joint and cause differences in strength depending on the type of adhesive. The different content of extractives in sapwood and red heartwood sometimes also called red heartwood or false core of beech can also extensively affect bondability of some adhesives by changed pH as suspected in some investigations (Vasiliki and Ioannis 2017).

This experiment aimed to verify the effect of the false heartwood on the strength of bonded joints by shear testing for commonly used thermoplastic and reactoplastic adhesives for the production of plywood intended for non-structural applications according to the relevant European standards and to further investigate in more detail whether false heartwood has the same effect on different types of adhesives.

EXPERIMENTAL

Specimen Preparation

A total of 8 variants of standardized beech samples with an average density of 692 kg/m^3 (ρ_8) were prepared for shear strength testing. Four types of adhesives were tested, PUR – Vinalep PUR bond D4 (STACHEMA CZ Ltd., Kolín, Czechia), phenol-formaldehyde (PF) – Lignofen G/3D (Lerg Ltd., Pustków, Poland), polyvinyl acetate (PVAc) – Würth 1K D4 (Würth Ltd., Künzelsau, Germany), urea-formaldehyde (UF) – Rakoll Isarit E1 (H.B. Fuller, Saint Paul (MN), United States) in two sample designs, with and without a false heartwood. The false heartwood samples were obtained from central parts of the 50-mm thick board according to discoloration. Only healthy parts were selected based on visual appearance. Sapwood samples were cut from the outer part without discoloration. Each of the samples was created slowly (est. 2 years) outdoors and samples were air-dried for a further 4 months indoors; beech lumber came from several different trees with origin in Czechia. Samples were transverse and longitudinally formatted into lamellas with dimensions of 500 × 50 × 5 mm^3 ± 0.1 mm, and their surface was subsequently modified by milling to the appropriate thickness. Before gluing, the beech boards were conditioned in standard atmospheric conditions, *i.e.*, at a temperature of 20 °C and a relative humidity of 65% for 10 days. The boards for bonding with PF and UF adhesive were dried to 8% to meet the conditions specified by the adhesive manufacturer. The plates prepared in this way were then glued two by one into panels with a 0.1 mm thin layer of the given adhesive with a coating of 160 g/m^2 and, to speed up the process, cured under heat in a single daylight press at a pressing pressure of 0.6 N/mm^2 according to the requirements of the adhesive manufacturers, which are listed in Table 1.

Table 1. List of Pressing Parameters According to Technical Documentation of Adhesives

Adhesive	**LIGNOFEN G/3/D**	**VINALEP PURBOND D4**	**RAKOLL ISARIT E1**	**WÜRTH 1K D4**
Producer	Lerg SA	Stachema CZ Ltd.	H.B. Fuller Austria	Würth Group
Base	Phenol-formaldehyde	Polyurethane	Urea-formaldehyde	Polyvinyl acetate
Application	one side	one side	one side	one side
Density (g/cm^3)	1.2	1	0.55	1.10
Spread (g/m^2)	160	160	160	160
Pressure (MPa)	0.8	0.2	0.6	0.6

Open assembly time (s)	600 to 1200	1200	900 to 1200	480 to 600
Pressing time (s)	720	4200	800	800
Pressing temperature (°C)	20	125	90	80

Samples with dimensions of 150 ± 0.5 mm × 20 ± 0.2 mm were subsequently formatted from these lamellae. Based on the data in EN 205 (2016), two 2.5 ± 0.5-mm-wide grooves with a spacing of 10 ± 0.2 mm in the middle of the length were added to the samples (Fig. 1). The dimensions of the surface of the glued joint are therefore 20 × 10 mm^2; however, each specimen was accurately measured with a digital caliper Kinex Iconic Labo 150 mm before testing.

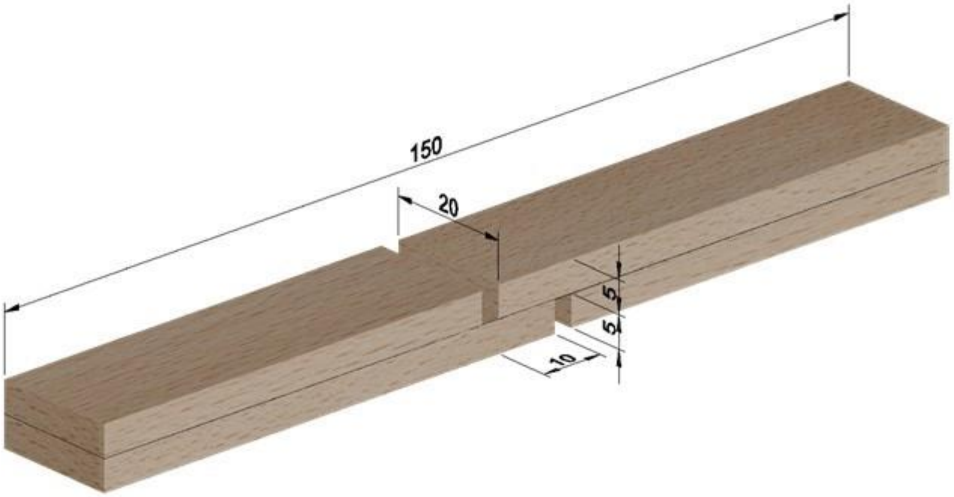

Fig. 1. Test specimen according to EN 205 (2016)

Conditioning of Specimen

The glued joint was conditioned depending on the type of the given adhesive according to the relevant standard. For reactive plastic adhesives PUR, the procedure was followed according to EN 12765 (2016). According to the adhesive durability class given by the manufacturer, the method of conditioning of the samples was determined according to EN 12765 (2016). For the urea-formaldehyde adhesive Rakoll Isarit E1 (H.B. Fuller), durability grade C2, it was necessary to test the samples conditioned in sequences 1 and 2; these conditions are shown in Fig. 2. The other two thermosetting adhesives, one based on polyurethane and the other based on phenol-formaldehyde, were tested to achieve durability level C4. This phase required the same two conditioning sequences as phase C2, and conditioning sequence 4 (Fig. 2).

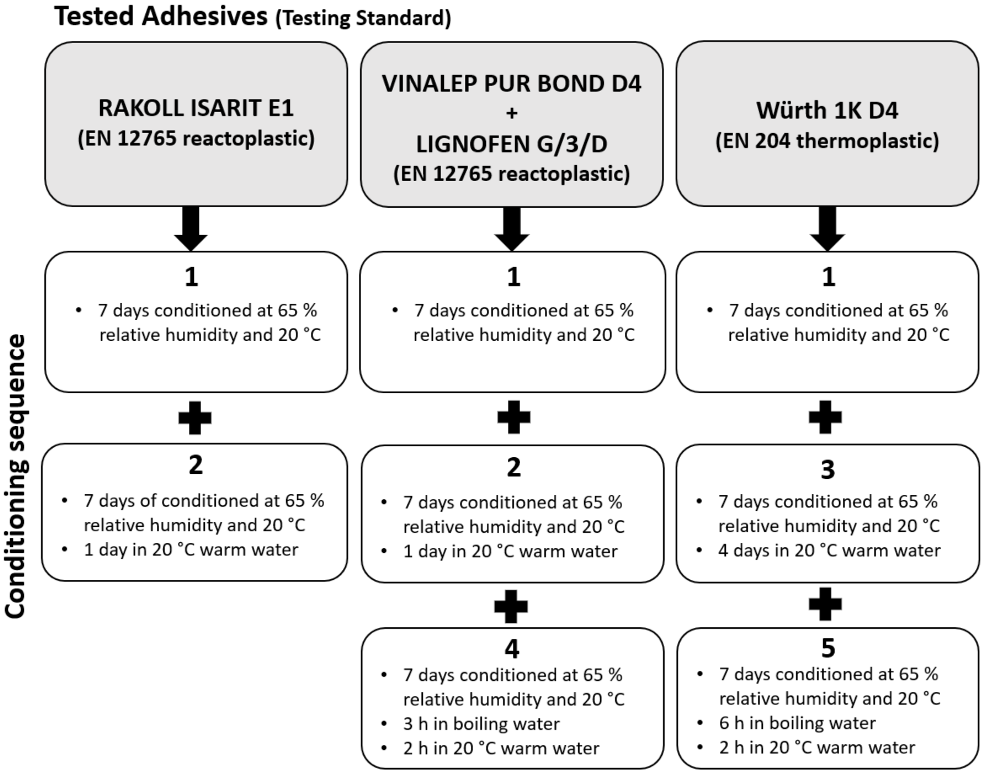

Fig. 2. Conditioning sequence definition

For the thermoplastic adhesive based on polyvinyl acetate, the samples were conditioned according to EN 204 (2016). The manufacturer declares the degree of moisture resistance D4 and, therefore, tests were carried out with conditioning sequences 1, 3, and 5, for which the conditions are shown in Fig. 2.

Tensile Shear Test

The conditioned and exposed samples were subsequently subjected to a tensile shear test to determine the shear strength of the glued joint. A TIRAtest 2850 testing device (TIRA GmbH, Schalkau, Germany), was used for this test. Jaws were mounted on the testing machine to clamp the test specimen in a wedge-like manner. The bodies were loaded with a constant feed rate. For thermoplastic adhesive Würth 1K D4 (Würth Ltd.), based on polyvinyl acetate, the loading speed was set to 50 mm/min, with failure occurring after 5 to 15 s. For reactoplastic adhesives, the loading speed was set to 10 mm/min, with joint failure occurring after 30 to 60 s. These tests were performed for all adhesives on beech samples with and without a false heartwood. The highest recorded force $F_{\max}$ (N), which the testing machine had to exert to tear the sample, was always monitored. This force was subsequently used to calculate the shear strength according to Eq. 1,

$$\tau = \frac{F_{\max}}{l_2 \times b} \tag{1}$$

where $F_{\max}$ is the applied maximum force (N), τ is the shear strength of the lap joint (MPa), l_2 is the length of the bonded test surface (mm), and b is the width of the bonded test surface (mm). Based on the results of the shear strength of the bonded joint, the adhesives were classified into durability class C1 to C4 according to the standard EN 12765 (2016) for reactoplastic adhesives (PUR, UF, PF). Thermoplastic polyvinyl acetate adhesive was then assigned in categories from D1 to D4 according to the EN 204 (2016) standard.

Experimental data were saved in MS Excel (Microsoft Corp., Redmond, WA, USA). Basic descriptive statistics, analysis of variance (ANOVA), and multiple comparison test Tukey's honestly significant difference (HSD) for unequal number of specimens were used for evaluation. All tests were performed at a significance level of $\alpha = 0.05$ in the Statistica 13.3 academic software (TIBCO, Tulsa, Oklahoma, USA).

RESULTS AND DISCUSSION

Beech samples with applied thermoplastic and reactive adhesives were subjected to a whole range of exposure levels according to EN 204 (2016) and EN 12765 (2016) standards, depending on the type of adhesive, and tested. From the results of the shear tests of polyvinyl acetate-based adhesive, where exposure levels 1, 3, and 5 according to the EN 204 (2016) standard, were applied, no significant difference was observed between beech samples with or without false heartwood according to the unequal N HSD test P_1=0,917; P_2=0,655; P_3=0,999; (lower index indicates respective conditioning sequence). For PVAc adhesive, the false heartwood of beech had no effect on the shear strength of the glued joint, as can be seen in Table 2.

No significant difference P_1=0,973; P_2=0,949; P_4=0,999 (lower index indicates respective conditioning sequence) in the shear strength of the glued joint of false heartwood and sapwood could be observed in samples based on phenol formaldehyde and urea formaldehyde (see Tables 3 and 4). The glued joints of the PF adhesive showed low shear strength in general, because the mean value for samples conditioned under standard conditions hardly met the standard limit. For the water immersion sequence, the values were even worse, and standard values have not been met. A possible cause of the decrease in shear strength values is the higher pH value of the beech wood (Albert *et al.* 1999), due to the oxidation of phenols. High pH negatively affects the hardening process of these two adhesives (Zhang *et al.* 2007) due to the electrostatic repulsion of hydroxyl groups at the protonation state (Zhao *et al.* 2022). In contrast, a more acidic environment enables the formation of branched structures terminated by a methyl group, which plays a key role in spatial cross-linking of urea-formaldehyde and phenol-formaldehyde adhesives (Gardziella *et al.* 2000; Pizzi and Ibeh 2022).

Table 2. Measured Values for PVAc 1C D4

Type of Sample	**Reference**			**False Heartwood**		
Conditioning sequence	1	3	5	1	3	5
Mean Value (MPa)	13.3	4.7	2.7	13.7	5.3	2.8
Max. (MPa)	14.5	5.9	2.9	16.9	6.5	3.8
Min. (MPa)	10.9	3.6	2.3	11.5	3.9	2.3
Standard Deviation (MPa)	1.1	0.6	0.2	1.9	0.9	0.4
Coefficient of Variance (%)	8	12	7	14	17	14

In Table 3, the urea-formaldehyde-based adhesive showed a higher shear strength for the sapwood samples, which means that there was a slightly negative effect of the false heartwood, although it was not shown to be statistically significant in the unequal N HSD test (P_1=0,281; P_2=0,850 (lower index indicates respective conditioning sequence). The UF adhesive samples, along with the other reactoplastic adhesives tested, also showed more variability than was the case with PVAc. This leads to weaker evidence for the negative influence of the false heartwood of beech on the shear strength of the glued joint. The results for exposure level 4 were unmeasurable, as expected with urea formaldehyde when the joint failed before it was put into the test machine.

Table 3. Measured Values for UF Isarit E1

Type of Sample	Reference			False Heartwood		
Conditioning sequence	1	2	4	1	2	4
Mean Value (MPa)	10.8	7.6	0	8.8	6.5	0
Max. (MPa)	14.4	11.9	0	11.8	9.5	0
Min. (MPa)	4.6	3.7	0	3.4	4.7	0
Standard Deviation (MPa)	3.4	2.5	0	2.8	1.4	0
Coefficient of Variance (%)	31	34	0	31	22	0

Table 4. Measured Values for PF Lignofen G3D

Type of Sample	Reference			False Heartwood		
Conditioning sequence	1	2	4	1	2	4
Mean Value (MPa)	9.9	5.9	4.9	10.7	5.0	5.2
Max. (MPa)	15.0	8.1	7.8	14.8	7.8	7.5
Min. (MPa)	5.7	3.6	1.9	6.7	2.6	1.5
Standard Deviation (MPa)	3.7	1.5	2.0	2.5	1.7	2.2
Coefficient of Variance (%)	37	25	40	24	34	43

The reference samples of UF met the strength condition for inclusion in the C2 resistance class, while the samples with a false heartwood do not even meet the minimum standard strength for inclusion in the C1 resistance class. The above-mentioned facts confirm the generally known difficulty of gluing beech wood (Aicher and Ohnesorge 2011a; Brunetti *et al.* 2019).

The PUR-based adhesive showed significantly lower shear strength values of false heartwood (P_2=0,0424) than the reference samples in the water immersion sequence (conditioning sequence 2) (see Table 5). The main reason for the reduced strength of false heartwood may be the dissolution of certain substances that are present in false heartwood. At the same time, the solubility rate of false heartwood compounds, such as quercetin glycosides, is faster at higher pH (Örtengren *et al.* 2001). In contrast, in acidic environments heartwood compounds exist in protonated form, so the solubility is much lower (Bouras *et al.* 2015; Chaves *et al.* 2020). It has been shown that PUR adhesives tend to foam more at higher pH (Maillard *et al.* 2021), leading to deeper penetration (Hass *et al.*

2012). All this leads to the formation of a starved bond line, which can be critical after the dissolution of heartwood compounds.

Table 5. Measurement Readings for Vinalep PUR Bond D4, C4

Type of Sample	**Reference**			**False Heartwood**		
Conditioning sequence	1	2	4	1	2	4
Mean Value (MPa)	13.0	5.3	4.1	12.3	3.3	4.5
Max. (MPa)	15.4	7.4	7.1	14.8	5.7	5.9
Min. (MPa)	9.9	2.4	2.2	10.4	0.8	3.6
Standard Deviation (MPa)	1.5	1.5	1.7	1.4	1.9	0.9
Coefficient of Variance (%)	12	28	40	12	57	19

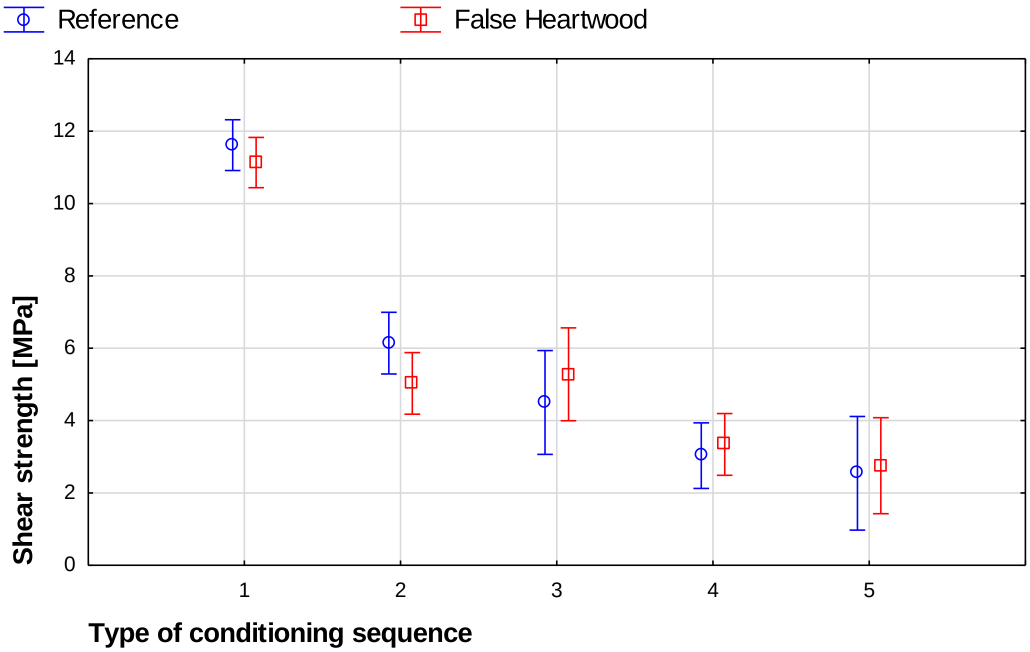

Fig. 3. General influence of false heartwood and conditioning sequence on shear strength of glue bond joint; Vertical bars denote a 0.95 confidence interval

For samples exposed to boiling water and then soaked in water, this difference was not apparent. The explanation probably lies in the duration of exposure to water. Although the movement of water in wood increases with higher temperature, the presence of tyloses, on the other hand, drastically reduces it (Rudman 1966), which increases the influence of the exposure time of the glued joint. Thus, the strength was reduced more for samples that have been in water for 24 h, and *vice versa* for samples that have been in boiling water for only 3 h and then in water at 20 °C for 2 h.

Overall, with the exception of PUR samples immersed in water, there was no remarkable difference between the heartwood and sapwood, as shown in Figs. 3 and 4, respectively.

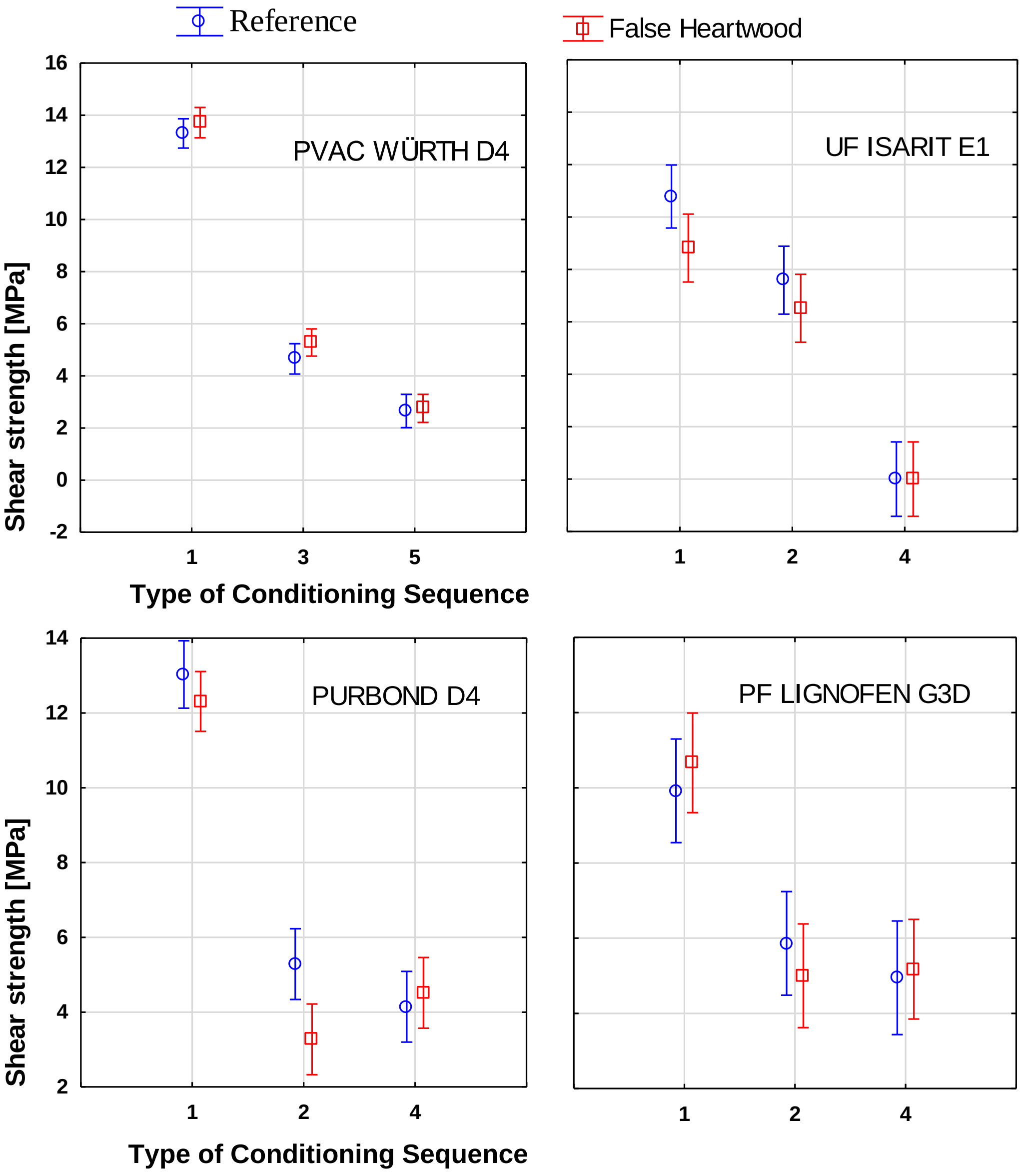

Fig. 4. Graphical image of glue bond shear strength of adhesives tested under different conditions; Vertical bars denote a 0.95 confidence interval

For the PVAc adhesive exposed to water for four days, a slightly better performance of false heartwood could be observed, which is not consistent with the theory of heartwood compound dissolution. This is because this type of adhesive forms predominantly physical bonds (Qiao and Easteal 2001) with wood and its penetration is not as deep as in PUR adhesives. These results are also in accordance with other tests (Hass *et al.* 2012) and

(Iždinský *et al.* 2020), where higher pH values show a slight but not significant increase in glue bond strength of the PVAc adhesive.

In general, the dry reference samples showed in approximately 40% of cases destruction in wood and not in the bond line, which means that actual bond line strength would be even higher in those cases. Water immersed specimen showed always failure in the bond line.

CONCLUSIONS

Adhesives of four different types were tested for the shear strength of the glued joints of beech sapwood and heartwood following current European standards.

1. According to the data obtained, there was no significant difference in the shear strength of the glued joints of beech sapwood and heartwood for the specimens prepared with the polyvinyl acetate (PVAc), urea-formaldehyde (UF), and phenol-formaldehyde (PF) adhesives.
2. The tests showed a significant difference in the shear strength of the glued joints for the polyurethane (PUR)-based adhesive after long-term immersion in water. After immersion in water, the mean shear strength of the reference sapwood specimens was 5.3 MPa and the shear strength of the heartwood specimens was almost 38% lower, *i.e.*, 3.3 MPa.
3. Moreover, in case of dry samples the failure zone of all adhesives joints was often in the wood, whereas in case of water-immersed samples the failure occurred always in the bond line.
4. When comparing destruction of dry false heartwood and sapwood specimen, false heartwood had a tendency to break in unexpected directions in some cases.
5. A possible significant influence of different pH of sapwood and false heartwood on PUR adhesives was observed but needs further investigation. It is however in accordance with tests made on other wood species rich in extractives (Hass *et al.* 2012; Vasiliki and Ioannis 2017). This leads to new hypothesis that for gluing of wood species with higher pH, PUR adhesives require some modification for ensuring proper bonding quality.
6. With the exception of PUR adhesives, beech wood with presence of false heartwood can be glued with the same technological process as beech wood without false heartwood.

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