Evaluation of Parameters Influencing the Withdrawal Strength of Oak and Beech Dowels

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The withdrawal strength of plain dowels with nominal diameter of 8 mm was compared with the spiral dowels manufactured from beech (*Fagus sylvatica* L.) and oak wood (*Quercus robur* L.). The test specimens were tested after conditioning at relative humidity (RH) 25%, 45%, 65%, and 85% at a constant temperature of 20 °C. Therefore, the influence of relative humidity (respective moisture content), dowel structure, and wood species of the dowels on the withdrawal strength was determined. The structure and low humidity (RH 25%) caused the highest strength (8.6 MPa) of spiral dowels. Compared to plain dowels, the higher withdrawal strength of spiral dowels was statistically significant. Adversely, the lowest withdrawal strength was found for plain beech dowels (3 MPa), which, in addition to higher relative humidity (RH 85%), was also caused by a combination of plain structure and greater diameter of the dowels, thereby decreasing the amount of adhesive in the bonded joint. The influence of the wood species of the dowels was not statistically significant overall.

Keywords: Dowel; Plain; Spiral; Beech; Oak; Polyvinyl acetate adhesive; Withdrawal strength; Relative humidity

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INTRODUCTION

Dowels are commonly used in the field of woodworking applications and construction (toys, furniture, timber roof trusses, *etc.*) as construction joints or as guide elements together with other fasteners such as confirmates, cam lock connectors, *etc.* In some cases, the dowels are exposed to various moisture conditions that can affect the mechanical properties of joints (Rammer and Winistorfer 2001; Tankut 2007; Bomba *et al.* 2014)

The strength of a bonded joint is a mechanical property that is determined by the strength of the adhesive, the strength of the wood, and the strength of the wood/adhesive interphase. The interphase is defined as an area of certain dimensions beginning in the bonded adherend material at a point where its properties (chemical, physical, mechanical, and morphological) begin to differ from those of the raw adherend. The interphase ends at the point of the adhesive where the local adhesive properties are again the same as the properties throughout the adhesive (Berglund and Rowell 2005)

It is possible to achieve a quality joint *via* three primary steps. The first step consists of the preparation of the surface so that the interaction between the adherend and the adhesive can be ensured. Surface treatment is usually mechanical or chemical, but both methods can be used at the same time. The second step is characterized by bonding the adhesive to the adherend surface. Due to the fact that binding at the molecular stage is required, the adhesive should be in the liquid state to achieve the required contact of both substances. The third step consists of assembling the joint, and this involves curing the adhesive (Frihart 2005, 2015).

The joints are typically considered as high quality, when after joint damage, there is a failure in the adherend, but not in the joint. However, such a quality joint is difficult to create with wood dowel joints. Individual research has already been conducted to determine the influence of wood species, moisture, joint type, the used adhesive, the thickness of the bonded joint, or the size of the bonded surface on the joint strength. Dowels are most often tested for withdrawal strength, which needs to be developed to withdraw the dowel from the support material (Jensen *et al.* 2001; Uysal and Özçifçi 2003; Seref *et al.* 2009; Yapici *et al.* 2011), or as a part of furniture constructions where members are joined to the shape of an “L” or “T” (Eckelman 1971; Eckelman *et al.* 2002; Tankut 2005).

The support material is usually a solid wood or composite material, *e.g.*, particle boards (PB) or medium-density fibreboards (MDF). When the withdrawal strength of dowels from solid wood is compared to the withdrawal strength from the PB (2.8 MPa) or MDF (4.4 MPa), less withdrawal strength overall was necessary (Seref *et al.* 2009). In these studies, the difference between the boards was explained by their different characteristics. The authors’ findings indicate that the withdrawal strength of the dowel joints changed due to several factors.

Some literature also discusses the differences between plain and spiral bars, or the influence of their length; however, these studies are focused mainly on metal bars (Chans *et al.* 2010). In addition to empirical testing, it is also possible to determine the withdrawal strength by analysing the elastic strain, thereby predicting it well (Eckelman and Cassens 1985; Jensen *et al.* 2001).

Oak and beech dowels were selected for the research because they are the two most common types of hardwood in Central Europe, and the dowels of these tree species are used in joints most often. Polyvinyl acetate adhesive (PVAc) was selected for bonding. PVAc adhesives are distinguished by their good affinity to wood and provide very strong and flexible joints. They are used mainly to bond solid wood, dowels and finish edges, and they are also used for veneering. Their advantages are in particular easy application, short hardening time, polymerization under normal pressure, and safety, because they do not contain formaldehyde (Bomba *et al.* 2018).

Dowels of different wood species with different surface structures that are exposed to loads at different moisture contents are used in furniture products and structural applications. The hypothesis is that all three factors have a major effect on the resulting joint strength. Therefore, the clarification of these relationships was the aim of this study.

EXPERIMENTAL

Materials

Beech test specimens with bonded dowel variants (Fig. 1) were tested in this research. Through the use of two types of dowels (plain and multigrooved spiral), two wood species of dowels (beech and oak), and 4 moisture stages (20 °C at 25%, 45%, 65%, 85%), for a total of 160 samples (2 × 2 × 4 × 10) were prepared. A total of 10 test specimens were prepared for each variant.

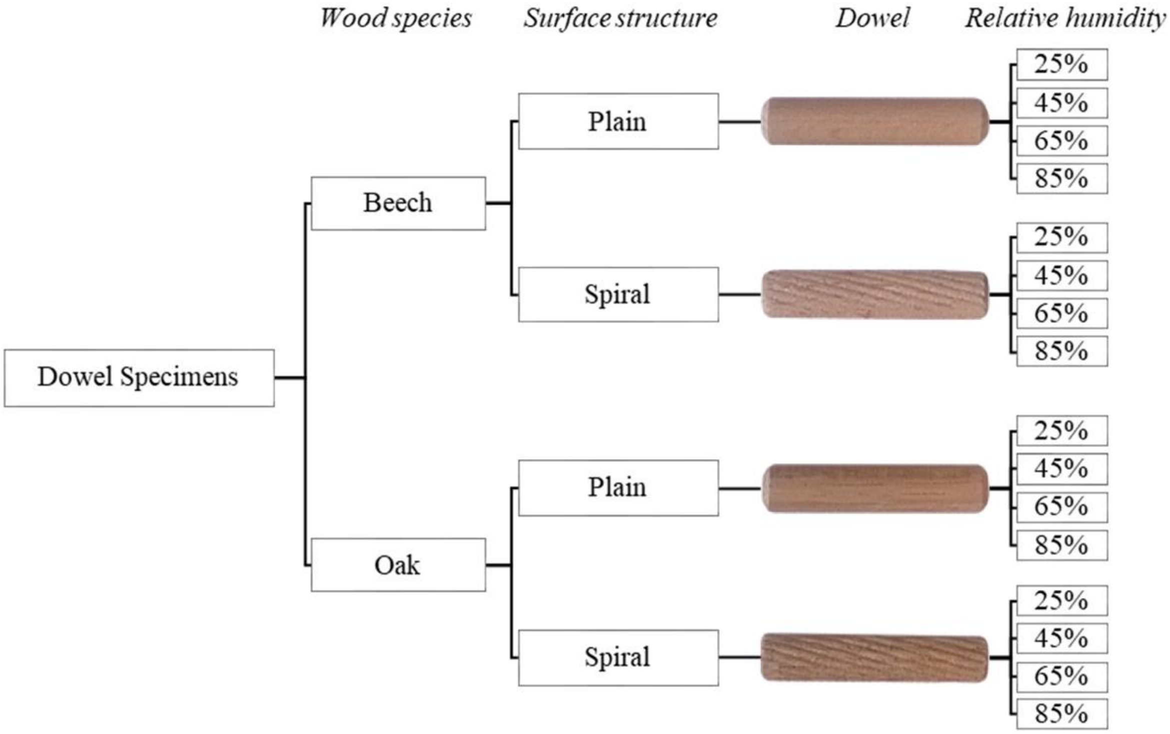

Fig. 1. Schematic diagram with tested dowels variants

The dowels had a cylindrical shape with nominal dimensions of 8 mm × 50 mm with chamfered edges (2 mm × 2 mm). The spiral dowels were purchased from a commercial manufacturer of dowels (Marušík Holz, Ostrava, Czech Republic). The plain dowels were made from 8-mm dowel rods (ASON-Vala, Most, Czech Republic). To calculate of the bonded surface area, the dimensions of the dowels were measured using a sliding scale (KINEX Measuring, Prague, Czech Republic).

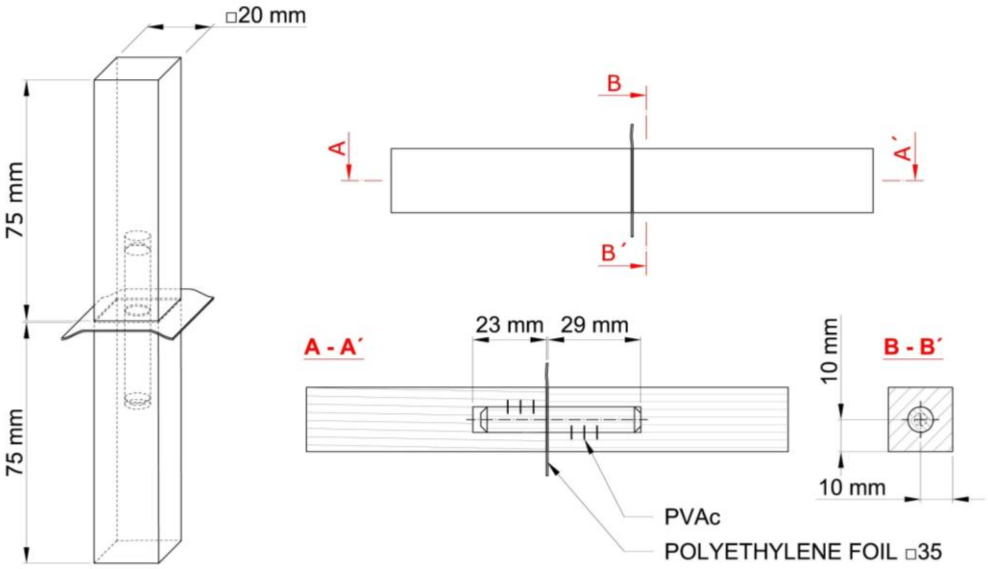

Fig. 2. Testing specimen configuration for withdrawal tests

Holes with an 8 mm diameter were drilled on a drilling machine VD 20 R (HOUFEK, Golčův Jeníkov, Czech Republic). A total of 0.3 g of adhesive was applied to a hole that was 29 mm deep, and 0.2 g was applied to a hole that was 23 mm deep. The dowels with the adhesive thus connected the two specimens lengthwise while being separated from each other by polyethylene foil. The dowels were first bonded to a deeper opening (29 mm) and then the second part was fitted. The moisture content of beech members was w = 8% as per ČSN 49 0103 (1979) and dry density corresponded to ρ_0 = 589 kg/m^3 as per ČSN 49 0108 (1993). The dry density of beech dowels was 594 kg/m^3 and dry density of oak dowels was 615 kg/m^3.

Polyvinyl acetate RAKOLL GXL 4 (H. B. Fuller Europe GmbH, Zurich, Switzerland), which falls into durability class D4 according to ČSN EN 204 (2017), was used as an adhesive. Through testing the adhesive according to ČSN EN 205 (2017) at conditioning sequence No. 1 (7 days at 20 ± 2 °C and relative humidity of 65 ± 5%), the shear strength of the adhesive was measured at 17 MPa (coefficient of variation 11%). Using a moisture analyser MB23 (Ohaus Corporation, Parsippany, NJ, USA), 51% solid content of adhesive was measured. The exact quantity of the adhesive in the holes was weighed on a laboratory scale PS 4500.R2 (RADWAG Váhy, Šumperk, Czech Republic) for each sample and spread over the bonded area. The other characteristics of the adhesive were taken from the manufacturer and measured at 20 °C: density 1 g/cm^3, pH 3.5, and viscosity of 5,500 mPa.s.

After the adhesive was applied, the testing specimens were clamped for 24 h and then placed into air conditioning chamber HPP750 (Memmert GmbH + Co. KG, Schwabach, Germany), where they were conditioned at a constant temperature of 20 ± 2 °C and four different relative humidities (RH): 25%, 45%, 65%, and 85 ± 5% to weight stabilization. Weight stabilization was considered to have been achieved when the weight of two consecutive weighings after 24 h did not differ by more than 0.1%. Afterward, according to standard ČSN 49 0103 (1979), the moisture content of beech members ($w_{25}/w_{45}/w_{65}/w_{85}$) was calculated for each stage to assess the impact of the moisture content. The weight of the samples conditioned in individual stages ($m_{25}/m_{45}/m_{65}/m_{85}$) and dried samples ($m_0$) was weighed on a laboratory scale (PS 4500.R2 (RADWAG Váhy, Šumperk, Czech Republic). The moisture content for the corresponding stage was then calculated using Eq. 1:

$$w_{25/45/65/85}\,(\%) = \frac{m_{25/45/65/85} - m_0}{m_0} \times 100 \tag{1}$$

After removal from the conditioning chamber, the test specimens were tested on a universal testing machine TIRA 50 kN (TIRA GmbH, Schalkau, Germany) in clamps that held the samples in the vertical position (Fig. 3). Upon completion of the test, the maximum applied force was measured by TIRAtest System 4.6.0.30 software (TIRA GmbH, Schalkau, Germany) ($F_{\max}$) and withdrawal strength was calculated according to Eq. 2 as the surface area (A) calculated based on the dowel diameter (d) and bonded length (h), where the failure occurred (Podlena *et al.* 2018):

$$\sigma\,(\text{MPa}) = \frac{F_{max}\,(N)}{A\,(mm^2)} = \frac{F_{max}\,(N)}{\pi d \times h\,(mm^2)} \tag{2}$$

Analysis of variance (ANOVA) of withdrawal strength at a 95% significance level ($\alpha = 0.05$), and multiple comparison test (Tukey HSD) were used to determine the statistical significance of the difference in variants using Statistica software (StatSoft, Version 13.3, Tulsa, OK, USA). The failure mode of the joint was also visually assessed according to the percentage representation of the given failure in the joint.

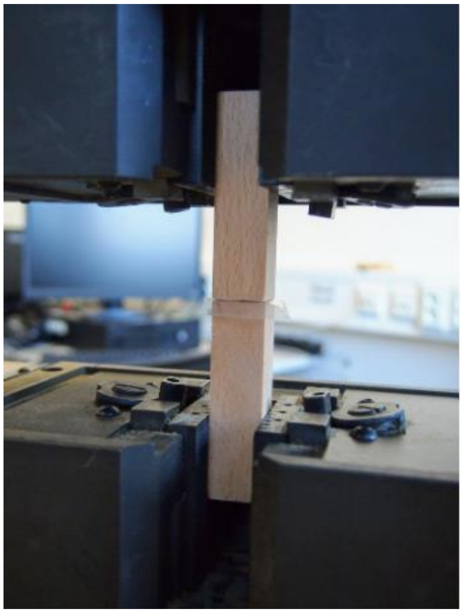

Fig. 3. Testing set-up used for withdrawal strength of dowels

RESULTS AND DISCUSSION

The summarized results of withdrawal strengths, which were obtained from testing dowels conditioned at a constant temperature of 20 °C and relative humidities of 25%, 45%, 65%, and 85%, are specified in Table 1.

Table 1. Withdrawal Strength of Tested Dowels According to the Relative Humidity

Wood Species	Beech								Oak							
Surface structure	Plain				Spiral				Plain				Spiral			
Relative Humidity (%)	25	45	65	85	25	45	65	85	25	45	65	85	25	45	65	85
Mean (MPa)	4.8	6.6	3.7	3.0	8.6	8.3	5.8	4.8	7.5	8.3	4.7	3.3	8.6	7.5	4.9	4.0
Median (MPa)	5.3	6.6	3.6	3.0	8.5	8.3	5.7	4.8	7.5	8.5	4.7	3.1	8.6	7.6	5.0	3.8
Standard Deviation (MPa)	1.2	0.8	0.6	0.7	1.0	0.5	1.3	1.0	1.2	1.2	0.8	0.8	0.8	1.4	0.5	0.9
Minimum (MPa)	2.5	5.7	3.1	2.0	7.1	7.5	3.2	3.5	5.6	6.1	3.3	2.5	7.5	4.5	4.1	2.8
Maximum (MPa)	6.2	8.3	4.9	4.0	10.6	9.1	7.9	6.0	9.8	9.7	6.4	5.0	9.9	9.1	5.6	6.1
Coefficient of Variation (%)	24	12	15	23	12	6	23	20	16	14	17	25	9	19	10	22

The results of ANOVA at a 95% significance level ($\alpha = 0.05$) are shown in Fig. 4. The highest average withdrawal strength was achieved by spiral beech and spiral oak dowels at RH 25% (8.6 MPa). The lowest strength values were achieved by plain beech dowels at RH 85% (3 MPa) with plain oak dowels (3.3 MPa).

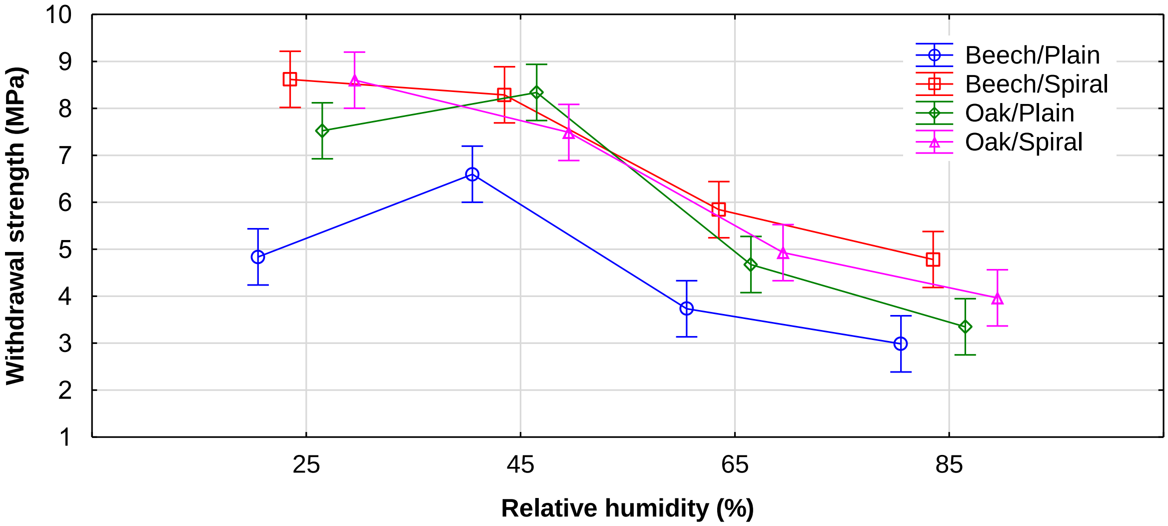

Fig. 4. Effect of dowel type and conditioning conditions on withdrawal strength. Vertical bars denote a 95% confidence intervals.

The results show that plain beech dowels reached the lowest values in all humidity levels. Although it is not entirely clear what caused the improvement in withdrawal strength of plain dowels when humidity increases from 25% to 45%, it can be assumed that this was due to the variability of the properties of the materials used, or due to the continued crosslinking reactions of the adhesive due to air humidity. In case of plain dowels, the shear strength of the adhesive is particularly important, as can be seen from the detailed analysis of failure modes. The failure modes of tested dowels are given in Table 2. The values in the table represent the average values obtained by visual assessment of each test specimen.

Table 2. Failure Modes of Tested Dowels

Wood Species		Beech								Oak							
Dowel Type		Plain				Spiral				Plain				Spiral			
Relative Humidity (%)		25	45	65	85	25	45	65	85	25	45	65	85	25	45	65	85
Failure Mode (%)	Dowel	4	10	8	2	79	72	66	12	11	7	10	1	68	67	40	52
	Beech Member	22	25	21	32	19	28	21	70	45	62	42	28	32	23	50	39
	Adhesive	75	65	72	67	3	0	14	19	44	32	49	72	0	11	11	10

Figure 5 shows the individual failure modes representing a given group of test specimens.

A detailed analysis of the failure modes shows that each evaluated parameter contributes to the failure in a different way. Some parameters may also interact, and the dowel diameter, or the thickness of the bonded joint may also affect the withdrawal strength.

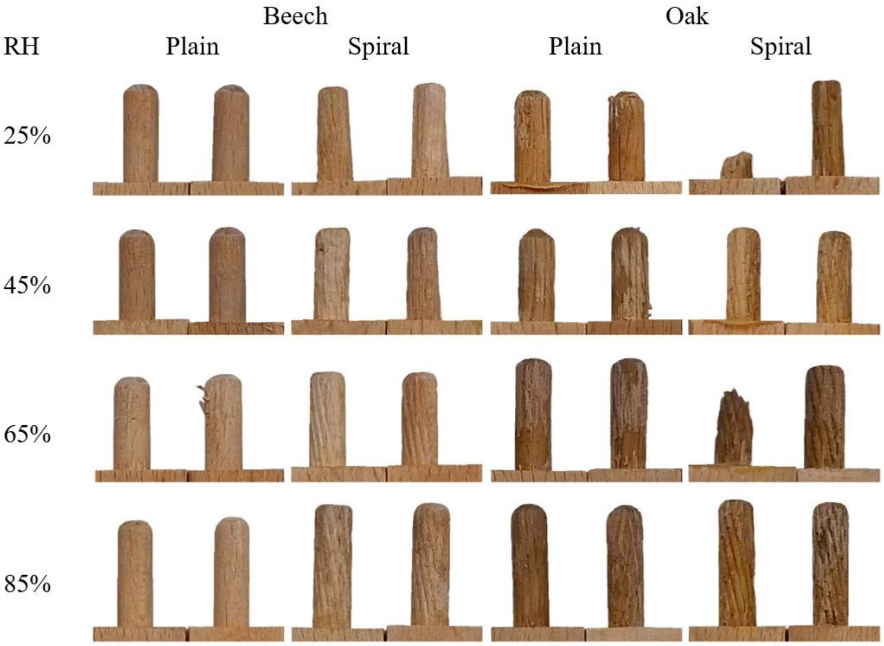

Fig. 5. Images of selected failure modes representing the tested dowels

The dowel diameters

Due to the fact that the used dowels were manufactured *via* machine production, the diameters of dowels had small coefficient of variations (0.6% to 1.2%). When comparing the diameter according to variants, a statistically significant difference was not found ($p > 0.05$) only between plain and spiral beech dowels (Fig. 6). The oak dowels had statistically significant different diameters between each other and the beech dowels as well ($p < 0.05$).

Table 3. Diameters of Tested Dowels Before Adhesive Application

Wood Species	Beech		Oak	
Surface Structure	Plain	Spiral	Plain	Spiral
Mean (mm)	7.99	8.00	7.82	7.70
Median (mm)	7.98	8.00	7.81	7.72
Standard Deviation (mm)	0.05	0.04	0.09	0.01
Minimum (mm)	7.82	7.90	7.65	7.40
Maximum (mm)	8.07	8.07	8.05	7.91
Coefficient of Variation (%)	0.6	0.5	1.2	1.2
Number of Valid Replications	40			

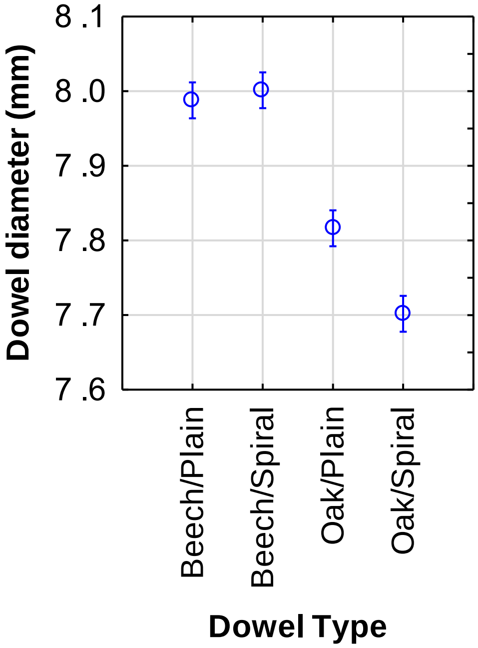

Fig. 6. Comparison of dowel diameters before adhesive application

In addition, the diameter of plain oak dowels (7.82 mm) and spiral-grooved dowels (7.7 mm) was most different from the declared diameter of 8 mm, which was specified by the manufacturer. With regard to oak spiral-grooved dowels, a 4% deviation of the diameter of the dowels was created.

Impact of relative humidity and wood moisture on withdrawal strength

In the range from RH 25% to RH 45%, the withdrawal strength of beech and plain oak dowels increased. Adversely, the strength of both spiral-grooved dowels in the area from RH 25% to 45% decreased. Otherwise, the withdrawal strength of dowels in all cases gradually decreased from RH 45%. Decreases in the strength of the bonded joint can be explained by the loss of adhesion of the PVAc adhesive, which occurred as wood moisture increased (Bomba *et al.* 2014). One of the main factors influencing the withdrawal strength was therefore relative humidity, or wood moisture due to hygroscopicity of wood.

Via air-conditioning to weight stabilization, on individual conditions, the moisture of the test specimens changed from 7% (RH 25%), 9% (RH 45%), 11% (RH 65%), and subsequently 16% (RH 85%). The initial moisture content of the beech specimens was an average of 8% prior to bonding. This means that in the first level (RH 25%), the average wood moisture dropped 1%, and it increased from the second stage. At wood densities of more than 8%, due to wood swelling, the dry dowel absorbed moisture from the adhesive and increased its volume in the joint in the hole. This principle was to ensure the maximum adherent bonded surface in the hole and result in a rigid bonded joint.

It can be seen from the assessment of the failure mode how higher moisture (RH 65% and in particular RH 85%) influenced the shear strength of the tested dowels. Therefore, the dowels remained intact and the remainder of the adhesive was visible on the surface of the dowels. When testing the dowels air-conditioned at 25% and 45% relative humidity, there was a partial breakdown of the wood structure.

Impact of dowel structure on withdrawal strength

Through an overall comparison of the withdrawal strength of plain and spiral-grooved dowels for both wood species (Fig. 7), it can be stated that spiral dowels provided statistically significant higher withdrawal strength compared to plain dowels ($p < 0.05$).

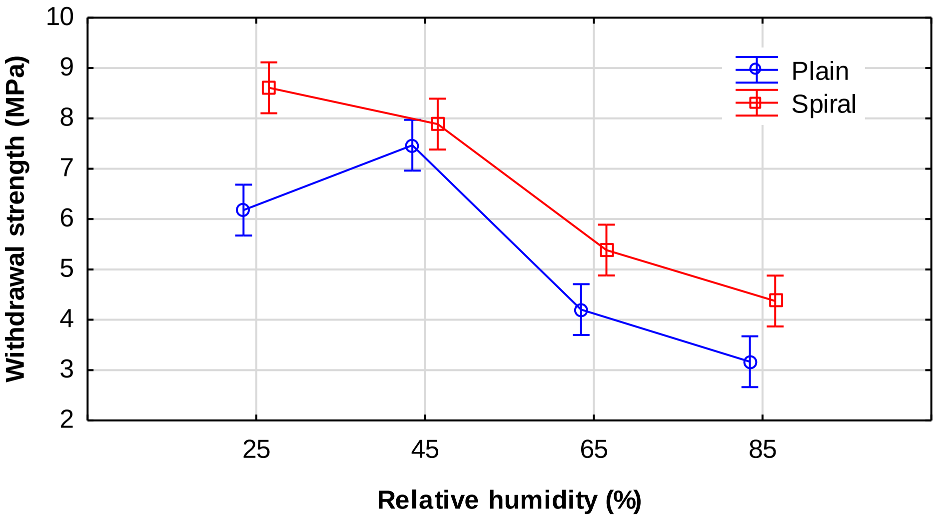

Fig. 7. Effect of surface structure and conditioning on withdrawal strength

According to the diameter of the dowels and the different surface structures of the dowels, it was possible to derive the principle of adhesive distribution during the insertion of dowels into the hole for the individual variants (Fig. 8).

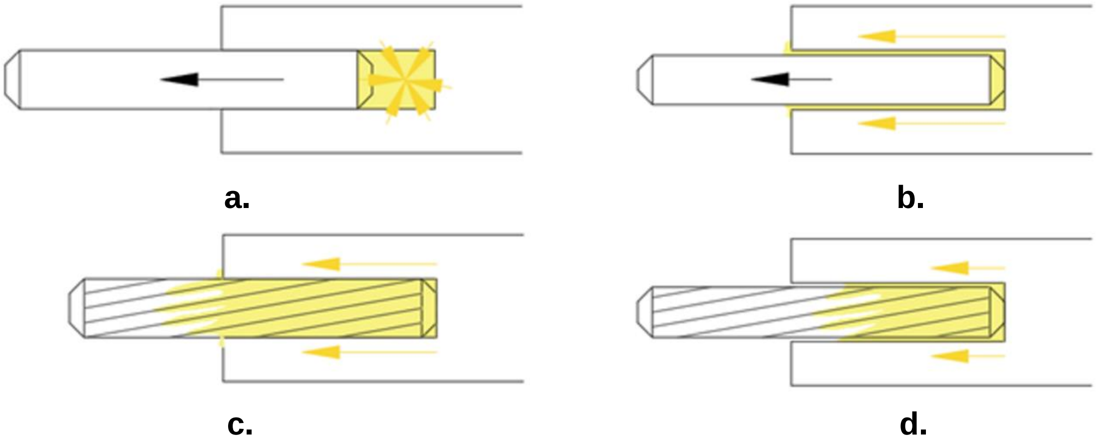

Fig. 8. Difference in adhesive distribution when dowels were inserted into the hole: beech/plain dowel (a), oak/plain (b), beech/spiral dowel (c), and oak/spiral dowel (d). The diagram was created based on a visual observation of the test specimens.

For plain dowels, the adhesive was usually wiped from the wall into the hole, where it was then air-locked. This was case of plain beech dowels, whose diameter was 7.99 mm (Fig. 8a). At the same time, a thin bond line was formed between the dowels and the 8 mm hole, which was not even the minimum (0.05 mm) required in the bonding theory (Landrock 2008). There was also a partial backward push of the dowels out of the hole, which was prevented by the withdrawal of the test specimens by clamps during the curing period of the adhesive.

The smaller diameter of plain oak dowels (7.82 mm) allowed for the leakage of the adhesive between the wall of the hole and dowel (Fig. 8b). Then, the bond line thickness for these plain dowels was greater. Therefore, it was likely that the diameters of tested dowels contributed to the overall higher strength of plain oak dowels.

In the second case, the pressure relief was facilitated by the grooves of the spiral dowels regardless of the outer diameter of the dowel. At the same diameter, during the insertion of the dowel into the hole, along with the air, the adhesive was led away from the hole *via* gaps in the grooves of the spiral dowels (Fig. 8c). Due to the grooves, the adhesive was also evenly distributed over the walls of the hole. This can explain why spiral-grooved dowels generally had better results compared to the plain dowels, both oak and beech. Furthermore, the higher resistance of spiral dowels can by influenced by additional mechanical transfer of load by surface projections.

For these reasons, it was not at all suitable to use plain dowels when bonding, and why grooved dowels (*e.g.*, spiral) should be given precedence in wooden structures. Although the chamfered edges of plain dowels helped remove the adhesive together with the air to the side, if the dowel had a larger diameter, then the adhesive was pushed from the hole. However, this may be an advantage compared to spiral dowels when they are, for example, used for particle boards, where the pressing of the adhesive between chips likely leads to strengthening the joint, which leads to higher withdrawal strength (Eckelman and Cassens 1985).

Impact of dowel wood species on withdrawal strength

In contrast, the overall impact of dowel wood species on withdrawal strength (Fig. 9) was not statistically demonstrated for the measurements ($p > 0.05$). In total, all of the beech and oak dowels were compared on all conditions for both structure's variants. However, the conclusion may be affected by the inclusion of dowels with a statistically significant difference in diameters ($p < 0.0$), where the beech dowels reached higher diameter than oak dowels (Fig. 5).

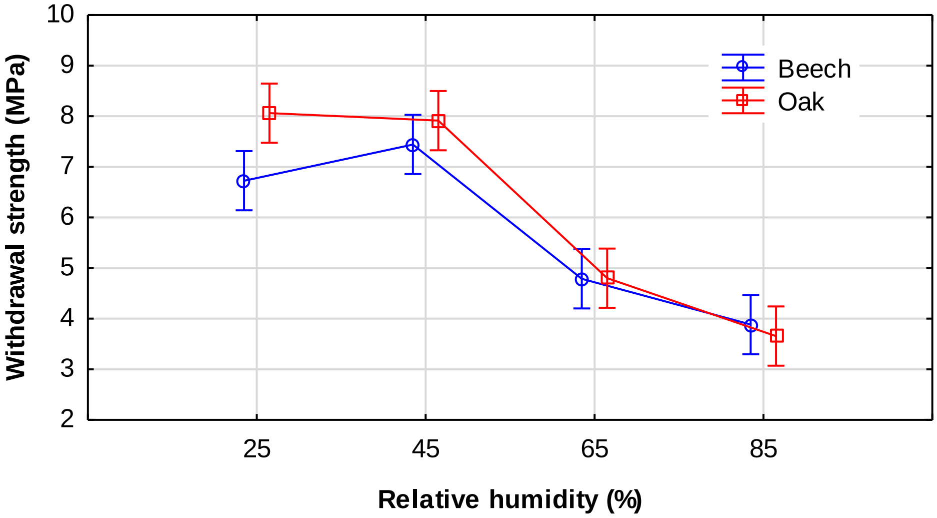

Fig. 9. Effect of dowel wood species and conditioning on withdrawal strength

İmirzi *et al.* (2015) also came to similar conclusions when comparing the strength of corner joints from Turkish beech (*Fagus orientalis* L.) and white oak (*Quercus alba*), which were bonded using a PVAc adhesive and two dowels from Turkish beech (*Fagus orientalis* L.). They were pulled out during the tests, and a small tensile difference (4%) in withdrawal strength between the wood species was observed.

CONCLUSIONS

1. A withdrawal strength of 8.6 MPa was measured equally as the highest for both the spiral beech and oak dowels at RH 25%, and this was due to the low relative humidity (RH 25%) and spiral structure of the dowels.
2. The lowest withdrawal strength of 3 MPa was measured for plain beech dowels, which was caused by higher relative humidity (RH 85%) in combination with tight dowels and a plain dowel structure.
3. In an overall comparison, spiral-grooved dowels achieved a higher withdrawal strength with a statistically significant difference compared to plain dowels ($p < 0.05$), thereby confirming the impact of the structure on withdrawal strength.
4. Through comparing the withdrawal strength of beech and oak dowels overall, a statistically significant difference between wood species was not proven ($p > 0.05$). This conclusion was observed for RH 45, RH 65, and RH 85% ($p > 0.05$) except RH 25% ($p < 0.05$).
5. The withdrawal strength of all of the tested dowels decreased with increasing relative humidity (from RH 45% to RH 85%).

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