Axial Loading of Different Single-pin Dowels and Effect on Withdrawal Strength

Milan Podlena, Štěpán Hýsek,* Jiří Procházka, Martin Böhm, and Jan Bomba

Withdrawal strengths of commercially available hardwood dowels were examined in this work. Multi-grooved dowels with a straight surface pattern and with pre-glued polyvinyl acetate (PVAc) were tested. Additionally, standard dowels with different single- and multi-grooved surface patterns were also tested, which were not pre-glued. Standard dowels were bonded with two types of PVAc and one type of polyurethane (PUR) adhesive. The influence of the type of dowel, the surface pattern, the dowel diameter, and the type of adhesive used on the dowel joint strength were investigated. Lower average strengths were observed for single-grooved dowels with a spiral pattern (4.9 MPa); failures generally occurred at the first or second thread of the spiral groove. For the pre-glued dowels, there were differences in the observed strengths, which depended upon how the PVAc adhesive was activated. Lower withdrawal strengths were noted for the pre-glued dowels when they were activated by dipping them in water (3.0 MPa) *versus* adding water directly to the pre-drilled holes (4.7 MPa to 5.4 MPa).

Keywords: Multi-grooved; Single-grooved; Pre-glued; Wood; Dowels; Withdrawal strength; Adhesive

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INTRODUCTION

Wooden dowels are one type of fastener for joints in wooden constructions. There are currently a wide range of types and sizes of wooden dowels available on the market. Their nominal dimensions are usually given in SI (Metric) or customary (English) units. To apply joints in structures, it is first necessary to understand their load bearing behavior to select the correct joint design with respect to the material parameters. For this study, some of the dowels have already been tested *via* the methods shown in Fig. 1.

The first group of methods are strength tests measuring the load bearing capacity of dowel joints under compression (Figs. 1a to 1c) and tension (Fig. 1d) under a bending moment. Dalvand *et al.* (2014) and Zhang and Eckelman (1993) ascertained that the diameter of the dowel and depth of penetration have a significant effect on the bending moment for tests under compression. For example with 19-mm plywood, the highest strength was achieved when increasing the dowel size from 6 mm to 8 mm. However, when the dowel size was increased to 10 mm, there was a decrease in the bending moment (Dalvand *et al.* 2014). When multi-pin dowel connection is used, it depends, in addition to the diameter and depth of the dowels, also on the number of dowels and their spacing (Derikvand and Ebrahimi 2015). Moreover, bending moment can be also derived during the testing of torsional strength (Fig. 1e). This method is a different case of dowel testing for furniture frames (Zhang *et al.* 2002b).

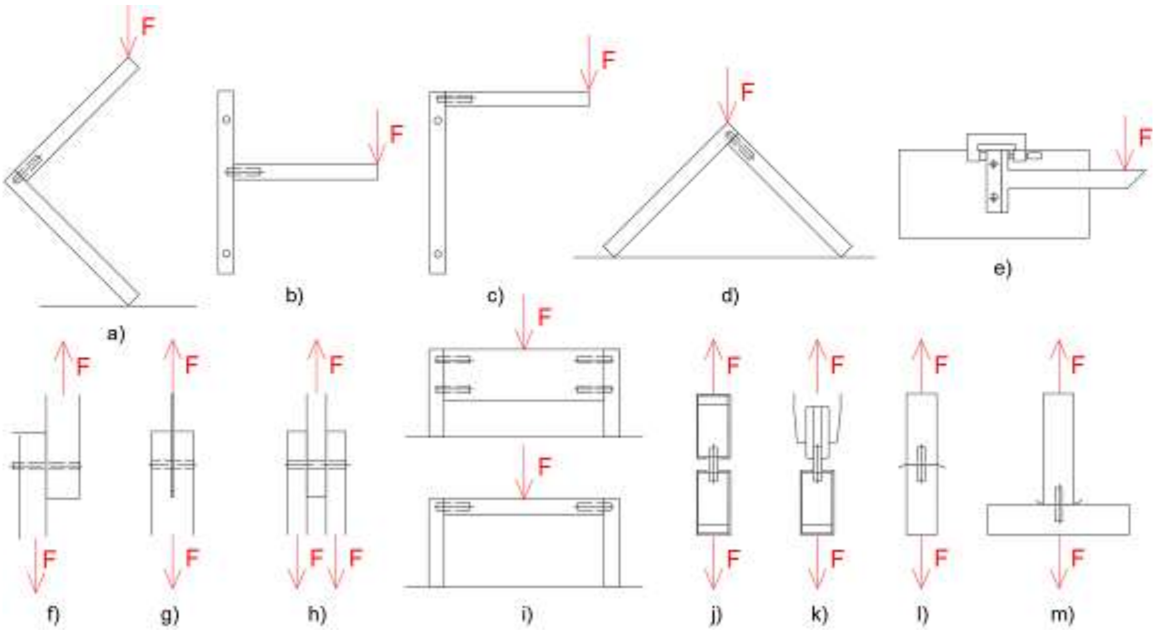

Fig. 1. Methods of dowel testing: a) Compression loading test of "L" type corner joint (Šimek *et al*. 2010; Dalvand *et al.* 2014; Derikvand and Ebrahimi 2015); b) Compression loading test of "T" type corner joint (Eckelman 1971, 1979; Zhang *et al.* 2001); c) Compression loading test of "L" type corner joint (Ahmad *et al.* 1993); d) Tension loading test of "L" type corner joint (Zhang and Eckelman 1993; Tankut 2005; Yerlikaya 2012); e) Torsional test (Zhang *et al.* 2002b); f) Single-shear test (Bocquet *et al.* 2007; Milch *et al.* 2017); g) Double-shear test (steel-to-timber) (Dorn *et al.* 2013); h) Double-shear test (timber-to-timber) (Santos *et al.* 2009; Oudjene and Khelifa 2010; Resch and Kaliske 2010); i) Lateral test test (Zhang *et al.* 2002a); j) Edge withdrawal test (Ahmad *et al.* 1993); k) Edge withdrawal test (Uysal 2005; Yapici *et al.* 2011; Özcan *et al.* 2013); l) Edge withdrawal test (Eckelman 1969; Jensen *et al.* 2001); and m) Face withdrawal test (Eckelman and Cassens 1985; Uysal 2005; Özcan *et al.* 2013)

Dowels are also often subjected to the shear stress in timber engineering (*e.g.*, beams) in two main stresses. The first is a single shear dowel-type joint (Figs. 1f) (Bocquet *et al.* 2007; Milch *et al.* 2017**)**. A shear plane is located between two members that are connected with a dowel. A double shear testing (Figs. 1g and 1h) has been tested in relation with steel-to-timber (Dorn *et al.* 2013) and with timber-to-timber connections (Santos *et al.* 2009; Oudjene and Khelifa 2010). These investigations tend to be analysed by finite element modeling that helps to determinate the load-carrying capacity without experimental testing (Santos *et al.* 2009; Oudjene and Khelifa 2010; Resch and Kaliske 2010). Moreover, Zhang *et al.* (2002a) reported about lateral shear strengths for horizontal and vertical rail directions for furniture applications (Fig. 1i).

Edge withdrawal tests (Figs. 1j to 1l), or face withdrawal tests (Fig. 1m), can be summarized in the last group of testing methods. For example, beech dowels with diameters of 6 mm, 8 mm, and 10 mm were used in the control samples of particleboard and medium-density fiberboard (MDF). The highest withdrawal strength was observed when using 6-mm dowels with particleboard, whereas for MDF, the highest strength was observed for 10-mm dowels (Kurt *et al.* 2009). This noted difference is explained by the boards' composition and their homogeneity. Of all of the above-mentioned tests, this method aptly measures the shear stress of dowels in different materials; hence, this method was selected for the testing of various dowels in this investigation.

EXPERIMENTAL

Materials

Rectangular prisms (20 mm × 20 mm × 75 mm) that were used to anchor the tested dowels were fabricated from beech wood (*Fagus sylvatica*) (Jaroslav Blažek, Roudnice nad Labem, Czech Republic). Prior to processing, the wood was left at room temperature (20 °C). The mass and volume of the test samples were determined and used to calculate density in accordance with ČSN 49 0108 (1993); the moisture content of the prisms was measured in accordance to ČSN 49 0103 (1979). These property values were ascertained once the sample mass was stabilized when the specimen was conditioned in a climate controlled chamber at 20 °C and 65% relative humidity.

Two rectangular prism members were axially connected using one dowel with an adhesive; a hole was drilled in the centre of each specimen to accommodate the dowel. Each hole was drilled using a horizontal drilling machine VD 20 R (Houfek, Golčův Jeníkov, Czech Republic) perpendicular to the prism face using a spiral drill bit (8-mm diameter) to a depth of 21 mm. A glued dowel was first inserted into the hole and pressed down to the bottom.

Then, the polyethylene film (30 mm × 30 mm × 0.2 mm) was rolled over the dowel. The film had an 8-mm circular hole made with a hollow punch tool. The film limits face-to-face gluing of the two prism members by excess adhesive extrusion during joint assembly. Hence, the withdrawal strength test is limited to shear stresses.

The test specimens were then clamped according to the configuration shown in Fig. 2 for 24 h for the adhesive to cure completely. The glued specimens were then conditioned in a constant climate chamber HPP750 (Memmert GmbH + Co. KG, Schwabach, Germany) at 20 °C and 65% relative humidity until constant mass was obtained.

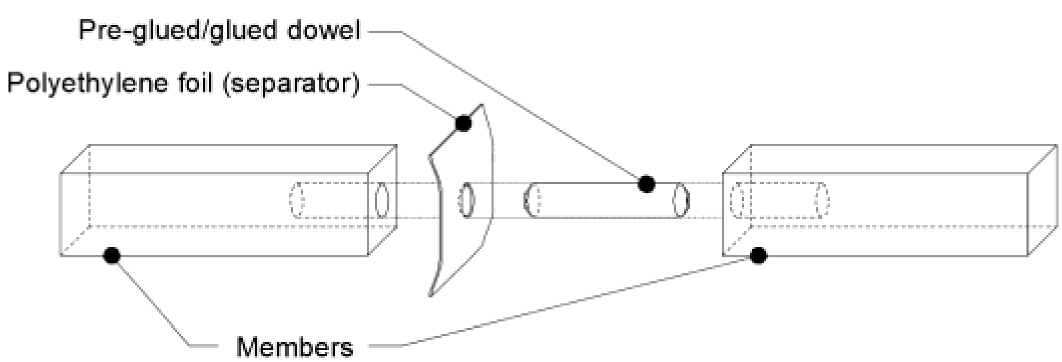

Fig. 2. Assembly of a typical test specimen used for the withdrawal test

The tested dowels had a cylindrical shape with a circular cross-section; the edges on the ends were chamfered (2 mm × 2 mm). Five hardwood dowels with different surface designs and characteristics were tested, all of which were obtained from commercial manufacturers (Table 1). A total of 12 test specimens was prepared for each series of the dowel. The dimensions of the dowels were checked using a sliding caliper (Kinex Measuring, Prague, Czech Republic) for calculating the surface area of dowels that are used for joint strength determinations.

Table 1. Designs and Characteristics of the Tested Dowels

Dowel Type	Surface Pattern		Adhesive	Wood Species	Dowel Dimension	Company and Location
Multi-grooved	Straight		Re-moisturizing PVAc (Pre-glued Dowel)	Beech	8 mm × 38 mm	HandyCT, Bridgeport, CT, USA
			Re-moisturizing PVAc (Pre-glued Dowel)		8 mm × 40 mm	KWB Germany GmbH, Stuhr, Germany
			None			Marušík Holz, Ostrava, Czech Republic
	Helical					
Single Grooved	Spiral			Maple	7.94 mm × 50.8 mm*	Rockler Woodworking and Hardware, Medina, MN, USA

* Reduced to 40 mm

Pre-glued dowels had applied re-moisturizing polyvinyl acetate (PVAc) adhesives on the surface, and they are activated when contacted with water. The adhesives were activated according to the instructions provided by the dowel's manufacturers. Pre-glued dowels manufactured by HandyCT were activated by water added directly to the hole of the prism member, which was filled to 1/3 of the hole's opening (*ca.* 0.35 mL) using a pipette. Alternatively, the dowels manufactured by KWB Germany GmbH were dipped for 5 s in water, allowed to drain for 5 s, and then inserted into the holes of the prism members to be joined.

When gluing standard dowels (*i.e.*, not pre-glued), the dowels and the holes of the prism members were coated with 0.2 g of the selected adhesive; the mass of the adhesive was weighed on a laboratory scale PS 4500.R2 (Radwag Váhy, Šumperk, Czech Republic). Two types of thermoplastic PVAc adhesives and one polyurethane (PUR) adhesive (Table 2) were examined. The glues are single-component adhesives and classified into durability grading according to the EN 204 (2001) standard. Tests of adhesives were performed in accordance to the EN 205 (2003) standard to measure and compare the differences in joint shear strengths.

Table 2. Classification of Dowel Adhesives Used in This Study from Product Datasheets

Adhesive Type	PVAc		PUR
Manufacturer and Location	H. B. Fuller Europe GmbH, Zurich, Switzerland	Adolf Würth GmbH & Co. KG, Künzelsau, Germany	Lear, Brno, Czech Republic
Product Name	Rakoll GXL 4	1K-Holzkaltleim D4	Lear D4
Durability Class	D4		D4 (C4)
Density	1 g/cm^3	1.1 g/cm^3	*
pH Value	*ca.* 3.5	*ca.* 3	*
Viscosity	5500 mPa·s	*ca.* 7000 mPa·s	4000 to 6000 mPa·s

* Not specified in manufacturer's datasheet

Methods

Dowel strength testing was performed using a TIRATEST 2850 universal testing machine (TIRA GmbH, Schalkau, Germany); measured values were recorded using TIRATEST System 4.6.0.40 software (TIRA GmbH, Schalkau, Germany). The testing machine was equipped with clamps for the standard tensile test (Fig. 3). Once the sample was clamped in the axis of the applied load force, a tensile force was applied to the test specimen by the machine. The crosshead speed was set to a constant 10 mm/min. During the tensile test, the stresses and strains were recorded, as well as the maximum force exerted (F_{max}) when the test joint failed. Tensile tests were conducted at a constant temperature of 20 °C; tests were performed on specimens that were immediately removed from the climate conditioning chamber.

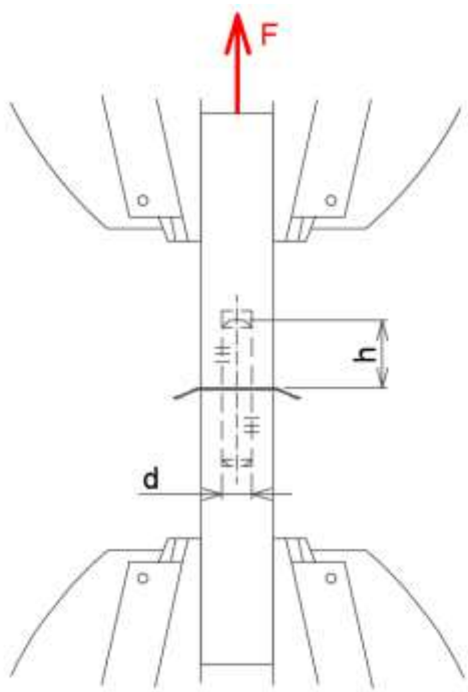

Fig. 3. Withdrawal strength test set-up of a sample with the universal testing machine

The withdrawal strength (σ), or shear stress, was calculated for each test specimen according to Eq. 1, based on the area of the surface area (A) from which the joint failed at F_{max}. The equation for calculating the withdrawal strength of the dowel is (Uysal 2005; Yapici *et al.* 2011; Özcan *et al.* 2013) as follows:

$$\sigma\ (MPa) = \frac{F_{max}\ (N)}{A\ (mm^2)} = \frac{F_{max}\ (N)}{2\pi r \times h\ \ (mm^2)} = \frac{F_{max}\ (N)}{2\pi\left(\frac{d}{2}\right) \times h\ \ (mm^2)} = \frac{F_{max}\ (N)}{\pi d \times h\ \ (mm^2)} \qquad (1)$$

The bonded surface area was based on the cylindrical shape of the dowel with height h (mm) and diameter d (mm) as shown in Fig. 3. The resulting data were analyzed using descriptive statistics and an analysis of variance (ANOVA) with Statistica computer software (StatSoft Inc., version 13.3, Tulsa, OK, USA). A one-way analysis of variance was used and the Tukey test was employed in order to determine the significant differences between group means. A significance level of α = 0.05 was used.

RESULTS AND DISCUSSION

The withdrawal strengths of the commercially available dowels of Table 1 were evaluated and compared in this study. The results are presented in Table 3. The dependence of withdrawal strengths of the dowels was influenced by the following factors: dowel type, surface pattern, adhesive type, and dowel diameter. The average density of the beech test specimens was 766 kg/m^3 when conditioned at 20 °C and 65% relative humidity; the moisture content of the specimens was 11.9%.

Table 3. Withdrawal Strength Results of the Tested Dowels

Dowel Type	Multi-grooved								Single Grooved		
Surface Pattern	Straight		Straight			Helical			Spiral		
Dowel Manufacturer	HandyCT	KWB Germany GmbH	Marušík Holz						Rockler Woodworking and Hardware		
Adhesive	Re-moisturizing PVAc (Pre-glued Dowel)	Re-moisturizing PVAc (Pre-glued Dowel)	Rakoll GXL 4	1K-Holzkaltleim D4	Lear D4	Rakoll GXL 4	1K-Holzkaltleim D4	Lear D4	Rakoll GXL 4	1K-Holzkaltleim D4	Lear D4
Mean (MPa)	4.7	3.0	6.7	6.6	7.5	6.9	7.9	6.8	4.9	4.9	6.0
Median (MPa)	4.6	2.8	6.5	6.3	7.8	6.7	7.9	6.8	5.1	4.9	6.3
Standard Deviation (MPa)	0.5	0.5	1.1	1.3	1.5	0.8	1.0	1.5	0.8	0.6	0.9
Minimum (MPa)	4.2	2.4	5.1	4.6	4.7	5.8	6.4	4.4	3.8	4.2	4.5
Maximum (MPa)	5.7	4.0	9.0	8.4	9.4	8.3	9.7	9.2	6.6	5.9	7.6
Coefficient of Variation (%)	10.3	16.9	16.6	19.2	20.4	11.2	13.0	21.7	17.1	11.9	15.4
Number of Valid Replications	12										

A one-way ANOVA was performed using a 95% significance level (α = 0.05) to ascertain statistical differences in withdrawal strengths of dowels from HandyCT (4.7 MPa) and KWB Germany GmbH (3.0 MPa) (Fig. 4). The ANOVA indicated that the withdrawal strength differences with these dowels were statistically significant. Both beech dowel designs were multi-grooved with a straight surface pattern, and they were conditioned to constant mass so that the moisture content was stabilized. In this case, these factors could be excluded from contributing to the withdrawal strength difference. Otherwise, different moisture content in the PVAc adhesive can decrease joint strength (Tankut 2007; Bomba *et al.* 2014). Before gluing, the color of re-moisturizing adhesives indicated that PVAc covers the entire surface of all dowels with a sufficient quantity of adhesive. However, the activation method of re-moisturizing PVAc adhesive was observed as a main effect to the withdrawal strength.

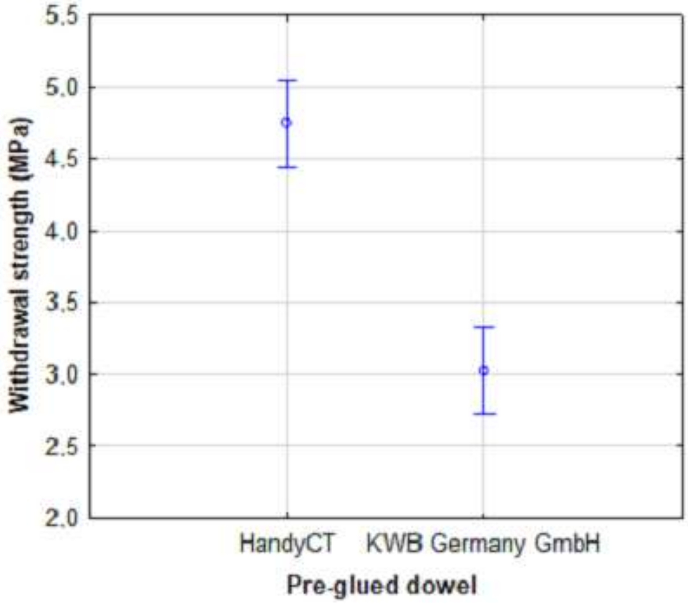

Fig. 4. Comparison of withdrawal strength of pre-glued dowels with one-way ANOVA at a 95% significance level ($\alpha = 0.05$)

The adhesive with pre-glued dowels from HandyCT was activated by water addition to the pre-drilled holes according to the instructions provided by HandyCT. The withdrawal strength of the pre-glued dowels from HandyCT (4.7 MPa) was statistically higher ($p < 0.05$) when compared to those from KWB Germany GmbH (3.0 MPa). According to the instructions from KWB Germany GmbH, the pre-glued PVAc adhesive on the dowel was activated by dipping the dowel in water. However, when the dowel was placed into the hole, the adhesive was wiped from the dowel's surface, and the adhesive remained at the edge at the top of the hole. It is visible in the section of test specimens after loading that adhesives did not leave any colour stain inside of the hole in comparison to the other application method (Fig. 5). Thus, the adhesive did not connect the dowel with the adherend and a poor bond was created, which resulted in a low withdrawal strength. Therefore, the dowels from KWB Germany GmbH were retested using the same glue activation method as dowels from HandyCT, *i.e.*, the adhesive was activated with water in the pre-drilled hole. This test confirmed that the method of activating the adhesive of pre-glued dowels affected its withdrawal strength. The withdrawal strength of KWB GmbH dowels increased to 5.4 MPa when the adhesive was activated *via* the addition of water into the hole. Due to the coloured adhesive, the section of test specimens shows how uniformly was the adhesives spread out over the entire area of the hole with an activation of PVAc in a hole (Fig. 5).

The shear strength of commercial adhesives on standard dowels without pre-gluing was performed on test specimens in accordance with the EN 205 (2003) standard under controlled conditions. It was observed that the strongest joints were obtained by using Rakoll GXL 4 adhesive (17.0 MPa), which was followed by 1K-Holzkaltleim D4 adhesive (13.7 MPa), followed by the weakest joints obtained with Lear D4 adhesive (11.8 MPa). A statistically significant difference was observed among these shear strength values ($p < 0.05$) using the various adhesives.

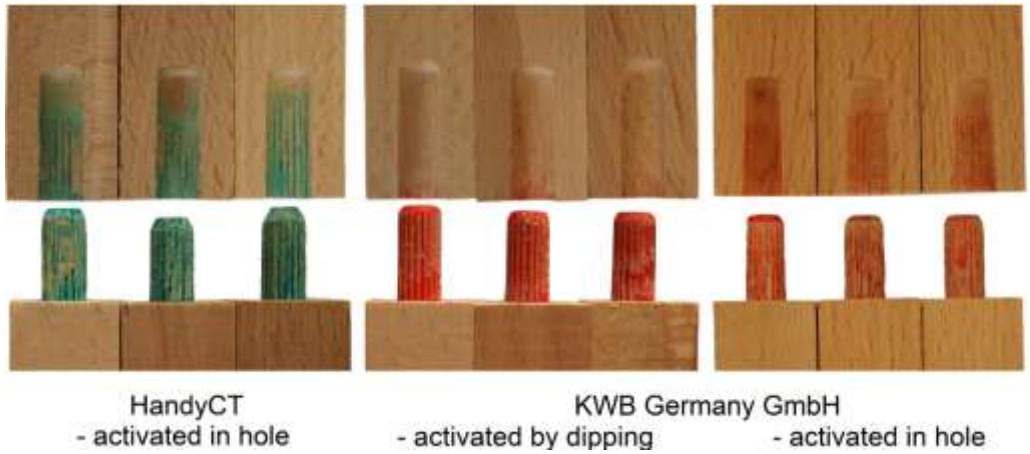

Fig. 5. Failure of pre-glued dowels

However, when collectively comparing the measured shear strengths of various dowel surface patterns (*i.e.*, straight, helical, and spiral) with the individual adhesives, it was observed that the specific adhesive used did not have a statistically significant effect on the strength of the dowel joints ($p > 0.05$). Hence, when comparing the withdrawal strength of the dowels, it is necessary to take into account other factors than just the adhesive used, such as the dowel's wood species, grooved surface pattern, and diameter.

A sufficient amount of commercial adhesive was always applied when preparing the test specimens, which was observed when excessive adhesive was expelled when inserting the dowel into the pre-drilled hole. This was especially observed for the PUR adhesive (Lear D4) as it foamed during its curing. This foaming of the PUR adhesive likely caused the high coefficient of variation of the withdrawal strength (15.4% to 21.7%) when compared to PVAc adhesives (11.2% to 19.2%), which has been suggested by Hýsek *et al.* (2018). The chamfered edges of all the dowels assisted in their complete insertion into the pre-drilled holes. Then, the adhesive was distributed to the sides of the hole through the different surface pattern of dowels.

The effect of the surface groove patterns of dowels manufactured by Marušík Holz was evaluated. Both multi-grooved dowels with straight and helical grooving were manufactured from beech wood where wood fibers were compressed. It helped to provide a better-bonded surface, due to the wood swelling. The most often observed cohesive failure mode was a combined failure, takingh place both in the adherend and in the adhesive layer. The same failure mode was observed for all tested adhesives. As can be seen, the fractions of adherend partially remained on the dowels after loading (Figs. 6a and 6b).

Multi-grooved dowels with a helical pattern had the highest average withdrawal strength value (7.9 MPa) when bonded with 1K-Holzkaltleim D4 (PVAc adhesive). In contrast, multi-grooved dowels with a straight pattern had a value 6.6 MPa, which was 16.5% lower than that of the helical pattern. The expectation was that the multi-grooved dowels with helical grooving will have the highest withdrawal strength of all tested dowels due to: the larger surface area, swelling of the compressed fibers, and the possibility of better adhesive layering on the surface. When the joints were bonded with Rakoll GXL 4 (PVAc adhesive), the multi-grooved dowels with a helical surface pattern yielded an average withdrawal strength that was only 2.9% higher than that of the multi-grooved dowels with a straight surface pattern (6.9 MPa *versus* 6.7 MPa, respectively).

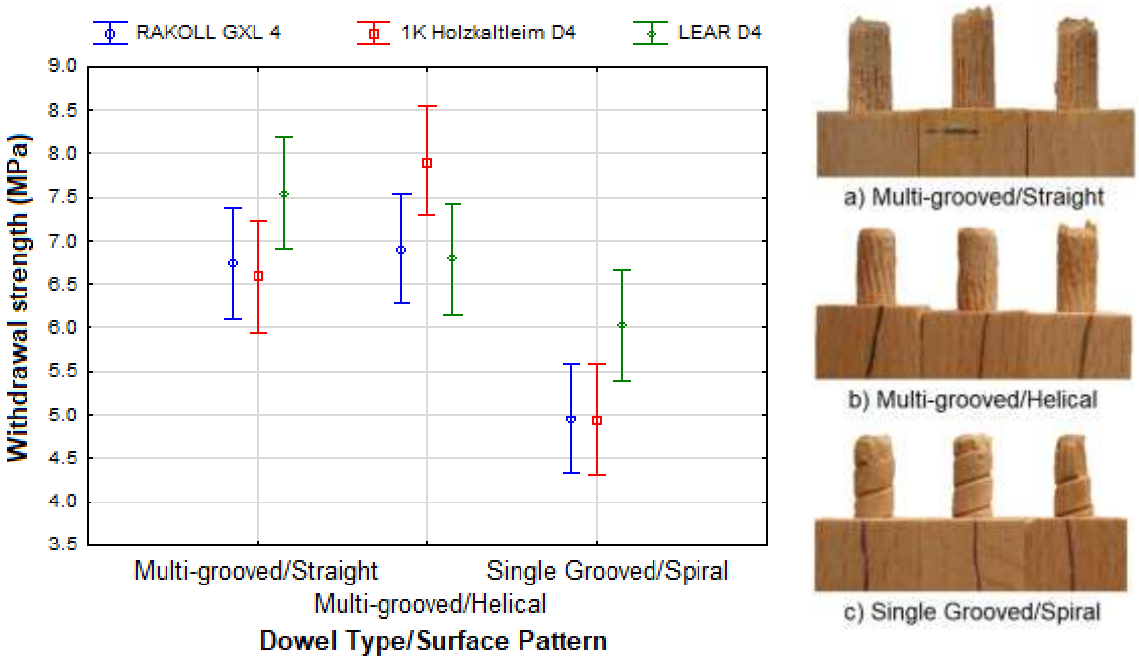

Fig. 6. Multiple means paired comparisons (*post hoc* Tukey test) of withdrawal strengths of dowel types at 95% significance level; failure mode of dowels (a – Multi-grooved/Straight; b - Multi-grooved/Helical; c – Single grooved/Spiral) bonded with Rakoll GXL 4 adhesive

In the case with the PUR adhesive (Lear D4), there was a 9.3% difference observed in the withdrawal strength of multi-grooved dowels with a straight *versus* helical surface pattern. A *post-hoc* data analysis was performed using Tukey's test of multiple paired means to determine the least significance difference (LSD) at the 95% level (α = 0.05). The results of this statistical analysis are presented in Table 4

Table 4. *P*-Values from Multiple Means Paired Comparisons from Table 3 Using the Tukey Test

		Multi-grooved /Straight			Multi-grooved /Helical			Single Grooved /Spiral		
		Rakoll GXL 4	1K-Holzkaltleim D4	Lear D4	Rakoll GXL 4	1K-Holzkaltleim D4	Lear D4	Rakoll GXL 4	1K-Holzkaltleim D4	Lear D4
Multi-grooved/ Straight	Rakoll GXL 4		1.000	0.684	1.000	0.195	1.000	**0.004**	**0.004**	0.805
	1K-Holzkaltleim D4	1.000		0.451	0.999	0.088	1.000	**0.013**	**0.012**	0.943
	Lear D4	0.684	0.451		0.882	0.996	0.744	**0.000**	**0.000**	**0.027**
Multi-grooved /Helical	Rakoll GXL 4	1.000	0.999	0.882		0.384	1.000	**0.001**	**0.001**	0.575
	1K-Holzkaltleim D4	0.195	0.088	0.996	0.384		0.237	**0.000**	**0.000**	**0.002**
	Lear D4	1.000	1.000	0.744	1.000	0.237		**0.003**	**0.003**	0.750
Single Grooved /Spiral	Rakoll GXL 4	**0.004**	**0.013**	**0.000**	**0.001**	**0.000**	**0.003**		1.000	0.308
	1K-Holzkaltleim D4	**0.004**	**0.012**	**0.000**	**0.001**	**0.000**	**0.003**	1.000		0.299
	Lear D4	0.805	0.943	**0.027**	0.575	**0.002**	0.750	0.308	0.299	

Statistical differences at 95% significance level in bold (P < 0.05)

The analysis indicated that there were no significant statistical differences (*i.e.*, $p > 0.05$) in strength among the multi-grooved dowels with straight *versus* helical patterns. When Ahmad *et al.* (1993) compared straight-grooved and spiral-grooved dowels, the highest withdrawal force was measured for spiral-grooved dowels. These dowels were manufactured from three various wood species (nyatoh, ramin, and rubberwood). A total difference 5.8% of average withdrawal force between spiral-grooved and straight-grooved dowels was measured. The same effect showed Eckelman and Cassens (1985) when dowels with various surface grooving were tested in two types of particleboards.

The worst performing dowels where those for which the adhesive was applied to the single-grooved spiral dowel. Figure 6c shows how the grooved spiral dowels failed. Although the shear strength of maple wood (11 MPa) is higher than beech wood (10 MPa) according to the DIN 68364 (2003) standard, the single-grooved spiral dowel made from maple was weaker than those dowels with a multi-grooved pattern made from beech, even with a low single-grooved angle. The joints made with single-grooved dowels always failed at the first to second thread, regardless of the type of adhesive used. The highest average strength of single-grooved spiral dowels was observed with the Lear D4 adhesive (6.0 MPa), likely due to foaming capability of PUR adhesives. Single-grooved spiral dowels bonded with both PVAc achieved 1.1 MPa less (4.9 MPa) than with PUR adhesive, and the difference was statistically significant ($p < 0.05$).

All of the tested dowels were commercially machine-made; their measured diameters (Table 5) had low coefficients of variations (0.7% to 1.1%), which indicated that the dowels were made with a high level of precision. The one-way ANOVA indicated that the diameters of pre-glued dowels from HandyCT and KWB Germany GmbH were significantly different ($p < 0.05$). In contrast, the diameters of multi-grooved straight and helical dowels (Marušík Holz) did not differ significantly ($p > 0.05$).

Table 5. Measured Diameters of the Tested Dowels Prior to Bonding

Dowel Type	Multi-grooved				Single Grooved
Pattern	Straight		Straight	Helical	Spiral
Dowel Manufacturer	HandyCT	KWB Germany	Marušík Holz		Rockler Woodworking and Hardware
Mean (mm)	8.11	8.01	7.93	7.93	7.86
Median (mm)	8.10	8.00	7.93	7.93	7.87
Standard Deviation (mm)	0.09	0.08	0.09	0.05	0.09
Minimum (mm)	7.97	7.90	7.65	7.8	7.67
Maximum (mm)	8.24	8.19	8.11	8.07	8.01
Coefficient of Variation (%)	1.1	1.0	1.1	0.7	1.1
Number of valid replicates	12		36		

The diameters of single-grooved dowels (7.86 mm) were the smallest amongst all the dowels tested; the manufacture of single-grooved dowels indicated they had a nominal diameter of 7.94 mm (*i.e.*, 5/16 in.) The manufacturers of the other dowel types indicated they had nominal diameters of 8 mm, whereas the measured diameters were between 7.65 mm for multi-grooved straight (Marušík Holz) to 8.24 mm for multi-grooved straight

(HandyCT (pre-glued)) dowels. The larger diameters for the pre-glued dowels were due to the applied adhesive layer on the dowels' surfaces, which resulted in tightly fitted joints being formed.

Differences in the diameters of the dowels also caused differences in the bond line thicknesses of the adhesive (up to 0.35 mm). However, the effect of the dowel diameters on withdrawal strengths was not statistically confirmed. Figure 7 illustrates this observation with multi-grooved dowels (with a straight pattern) glued with PVAc adhesives (R^2 = 0.10 and R^2 = 0.23). When testing different bond line thicknesses (0.01 mm to 0.10 mm) in dowel joints, Ratnasingam and Ioras (2015) reported that the highest fatigue and static strength is achieved with the smallest bond line thicknesses (0.01 mm) using a PVAc adhesive. Bomba *et al.* (2018) noted that the shear strength of joints with dowels, which were tested in accordance to EN 205 (2003), decreased as the bond line thickness of D4 grade adhesives was lowered from 0.5 mm to 0.1 mm. Therefore, the diameter of the single groove dowels in combination with a single groove as the primary influence on low withdrawal strength.

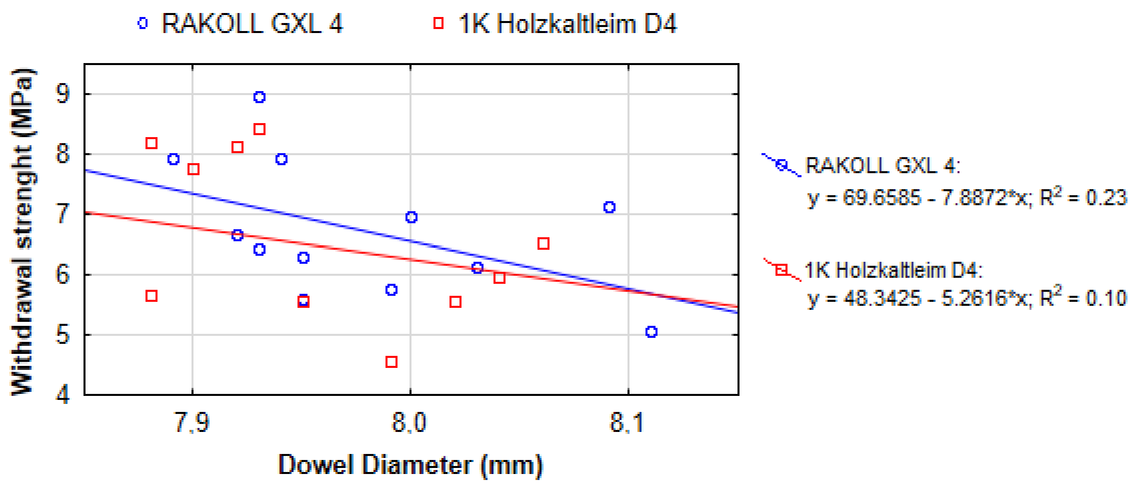

Fig. 7. Dependence of withdrawal strength on the diameter of multi-grooved dowels with a straight pattern (Marušík Holz) when using commercial PVAc adhesives

CONCLUSIONS

1. The highest average withdrawal strength (7.9 MPa) with the tested adhesives was measured for standard multi-grooved dowels with a helical pattern (Marušík Holz) with a PVAc adhesive (1K-Holzkaltleim D4).
2. When comparing dowels with the same commercial adhesive, single-grooved dowels with a spiral pattern (Rockler Woodworking and Hardware) and glued with PVAc adhesive (Rakoll GXL 4 and 1K-Holzkaltleim D4) had the lowest average withdrawal strength (4.9 MPa). Failure typically occurred after the first to second thread of the groove.
3. The differences in the withdrawal strengths of dowels with different multi-grooved patterns (straight and helical) were not statistically significant (p > 0.05) for any of the three adhesives tested.

4. The pre-glued dowels from KWB Germany GmbH were dipped for activation of the PVAc adhesive, which led to a visible wiping-off of the adhesive when the dowel was inserted, creating a poor bond, and thus resulting in a lower strength (3.0 MPa) compared to dowels from HandyCT (4.7 MPa) that were activated by the water from the hole.
5. However, the dowels from KWB Germany GmbH had a 44% higher withdrawal strength (5.4 MPa *vs.* 3.0 MPa) when activating the pre-glued adhesive using the instructions provided by HandyCT instead of those provided by KWB Germany GmbH.

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REFERENCES CITED

Ahmad, S., Amin, A. H., Ali, R., and Tahir, H. M. (1993). "Withdrawal and bending strengths of dowels from three Malaysian timbers," *J. Trop. For. Sci.* 6(1), 74-80.

Bocquet, J., Pizzi, A., Despres, A., Mansouri, H. R., Resch, L., and Michel, D. (2007). "Wood joints and laminated wood beams assembled by mechanically-welded wood dowels," *J. Adhes. Sci. Technol.* 21(3-4), 301-317. DOI: 10.1163/156856107780684585

Bomba, J., Šedivka, P., Böhm, M., and Devera, M. (2014). "Influence of moisture content on the bond strength and water resistance of bonded wood joints," *BioResources* 9(3), 5208-5218. DOI: 10.15376/biores.9.3.5208-5218

Bomba, J., Šedivka, P., Hýsek, Š., Fáber, J., and Oberhofnerová, E. (2018). "Influence of glue line thickness on the strength of joints bonded with PVAc adhesives," *Forest Prod. J.* (in press). DOI: 10.13073/FPJ-D-17-00038

ČSN 49 0103 (1979). "Drevo. Zisťovanie vlhkosti pri fyzikálnych a mechanických skúškach [Wood. Determination of moisture content at physical and mechanical testing]," Vydavatelství úřadu pro Normalizaci a Měření [Publishing of the Office for Standards and Metrology], Prague, Czech Republic.

ČSN 49 0108 (1993). "Drevo. Zisťovanie hustoty [Wood. Determination of density]," Vydavatelství úřadu pro Normalizaci a Měření [Publishing of the Office for Standards and Metrology], Prague, Czech Republic.

Dalvand, M., Ebrahimi, G., Tajvidi, M., and Layeghi, M. (2014). "Bending moment resistance of dowel corner joints in case-type furniture under diagonal compression load," *J. Forest Res.* 25(4), 981-984. DOI: 10.1007/s11676-014-0481-y

Derikvand, M., and Ebrahimi, G. (2015). "Rotational stiffness of L-shaped dowel," in: *27th International Conference Research for Furniture Industry*, Gazi University, Ankara, Turkey.

DIN 68364 (2003). "Kennwerte von Holzarten - Rohdichte, Elastizitätsmodul und Festigkeiten [Characteristics of wood species - bulk density, modulus of elasticity and

strengths],” Deutsches Institut für Normung [German Institute for Standardization], Berlin, Germany.
Dorn, M., De Borst, K., and Eberhardsteiner, J. (2013). “Experiments on dowel-type timber connections,” *Eng. Struct.* 47, 67-80. DOI: 10.1016/j.engstruct.2012.09.010
Eckelman, C. A. (1969). “Engineering concepts of single-pin dowel joint,” *Forest Prod. J.* 19(12), 52-60.
Eckelman, C. A. (1971). “Bending strength and moment-rotation characteristics of two-pin moment resisting dowel joints,” *Forest Prod. J.* 21(3), 35-39.
Eckelman, C. A. (1979). “Out-of-plane strength and stiffness of dowel joints,” *Forest Prod. J.* 29(8), 32-38.
Eckelman, C. A., and Cassens, D. L. (1985). “Withdrawal strength of dowels from wood composites,” *Forest Prod. J.* 35(5), 55-60.
EN 204 (2001). “Classification of non-structural adhesives for joining of wood and derived timber products,” European Committee for Standardization, Brussels, Belgium.
EN 205 (2003). “Adhesives – Wood adhesives for non-structural applications-Determination of tensile shear strength of lap joints,” European Committee for Standardization, Brussels, Belgium.
Hýsek, Š., Šedivka, P., Böhm, M., Schönfelder, O., and Beran, R. (2018). “Influence of using recycled polyurethane particles as a filler on properties of polyurethane adhesives for gluing of wood,” *BioResources* 13(2), 2592-2601. DOI: 10.15376/biores.13.2.2592-2601
Jensen, J. L., Koizumi, A., Sasaki, T., Tamura, Y., and Iijima, Y. (2001). “Axially loaded glued-in hardwood dowels,” *Wood Sci. Technol.* 35(1-2), 73-83. DOI: 10.1007/s002260000076
Kurt, S., Uysal, B., Özcan, C., and Yildirim, M. N. (2009). “The effects of edge banding thickness of uludag bonded with some adhesives on withdrawal strengths of beech dowel pins in composite materials,” *BioResources* 4(4), 1682-1693. DOI: 10.15376/biores.4.4.1682-1693
Milch, J., Tippner, J., Brabec, M., Sebera, V., Kunecký, J., and Kloiber, M. (2017). “Experimental testing and theoretical prediction of traditional dowel-type connections in tension parallel to grain,” *Eng. Struct.* 152, 180-187. DOI: 10.1016/j.engstruct.2017.08.067
Oudjene, M., and Khelifa, M. (2010). “Experimental and numerical analyses of single double shear dowel-type timber joints,” in: *World Conference on Timber Engineering 2010*, Trees and Timber Institute, National Research Council, Sesto Fiorentino, Italy, pp. 476-481.
Özcan, C., Uysal, B., Kurt, S., and Esen, R. (2013). “Effect of dowels and adhesive types on withdrawal strength in particleboard and MDF,” *J. Adhes. Sci. Technol.* 27(8), 843-854. DOI: 10.1080/01694243.2012.727157
Ratnasingam, J., and Ioras, F. (2015). “The fatigue characteristics of two-pin moment-resisting dowel furniture joints with different assembly time and glueline thickness,” *Eur. J. Wood Wood Prod.* 73(2), 279-281. DOI: 10.1007/s00107-015-0886-0
Resch, E., and Kaliske, M. (2010). “Three-dimensional numerical analyses of load-bearing behavior and failure of multiple double-shear dowel-type connections in timber engineering,” *Comput. Struct.* 88(3-4), 165-177. DOI: 10.1016/j.compstruc.2009.09.002
Santos, C. L., Jesus, A. M. P., Morais, J. J. L., and Lousada, J. L. P. C. (2009). “Quasi-

static mechanical behaviour of a double-shear single dowel wood connection," *Constr. Build. Mater.* 23(1), 171-182. DOI: 10.1016/j.conbuildmat.2008.01.005

Šimek, M., Haviarová, E., and Eckelman, C. (2010). "The end distance effect of knock-down furniture fasteners on bending moment resistance of corner joints," *Wood Fiber Sci.* 42(1), 92-98.

Tankut, A. N. (2005). "Optimum dowel spacing for corner joints in 32-mm cabinet construction," *Forest Prod. J.* 55(12), 100-104.

Tankut, N. (2007). "The effect of glue and glueline thickness on the strength of mortise and tenon joints," *Wood Res.* 52(4), 69-78.

Uysal, B. (2005). "Withdrawal strength of various laminated veneer dowels," *Wood Fiber Sci.* 37(2), 213-219.

Yapici, F., Likos, E., and Esen, R. (2011). "The effect of edge banding thickness of some trees on withdrawal strength of beech dowel pins in composite material," *Wood Res.* 56(4), 601-612.

Yerlikaya, N. Ç. (2012). "Effects of glass-fiber composite, dowel, and minifix fasteners on the failure load of corner joints in particleboard case-type furniture," *Mater. Des.* 39, 63-71. DOI: 10.1016/j.matdes.2012.02.024

Zhang, J., Erdil, Y. Z., and Eckelman, C. A. (2002a). "Lateral holding strength of dowel joints constructed of plywood and oriented strandboard," *Forest Prod. J.* 52(7/8), 83-89.

Zhang, J., Erdil, Y. Z., and Eckelman, C. A. (2002b). "Torsional strength of dowel joints constructed of plywood and oriented strandboard," *Forest Prod. J.* 52(10), 89-94.

Zhang, J.-L., and Eckelman, C. A. (1993). "The bending moment resistance of single-dowel corner joints in case construction," *Forest Prod. J.* 43(6), 19-24.

Zhang, J.-L., Quin, F., and Tackett, B. (2001). "Bending strength and stiffness of two-pin dowel joints constructed of wood and wood composites," *Forest Prod. J.* 51(2), 29-35.

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