Ultimate Direct Withdrawal Loads of Low Shear Strength Wooden Dowels in Selected Wood Species for Furniture Applications

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The wood dowel pin is one of the common fasteners for connecting structural members in wooden furniture frame construction, such as chairs. The effects of dowel penetration depth, shear strengths of connection member and dowel materials, dowel surface texture, and member grain orientation on ultimate direct withdrawal loads of single dowels withdrawn from wooden materials were investigated. The main findings were that the connections using dowels and main members with low shear strength properties achieved the same ultimate direct withdrawal loads with connections using the materials with higher shear strength properties for dowels and main members. Additionally, the existing empirical equations, including shear strength properties for both dowel and main member materials used to construct dowel connections, tended to remarkably underestimate the ultimate direct withdrawal loads of the evaluated dowel connections withdrawn from the end and side grains of the tested wood species. The connection main members in this study when these two shear strength values were added together was less than 25 MPa. Both estimation expressions were modified to consider the lower shear strength effort on ultimate direct withdrawal loads of dowels evaluated in this experiment.

Keywords: Dowel pins; Direct withdrawal loads; Shear strength; Penetration depth; End grain; Side grain

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INTRODUCTION

Dowel pins have been one of the most commonly used connectors in the furniture industry for joining wooden structural members in furniture frame construction. An axial tensile load is the common force acting on a dowel pin connecting two furniture frame structural members, such as a side rail to a back post in a chair. Therefore, the direct withdrawal load capacity of a dowel pin connection needs to be researched and understood so that dowel connections can be designed and engineered to be able to safely carry tensile forces.

Eckelman (1969) studied the effect of dowel length and diameter on ultimate direct withdrawal loads of single dowels from different solid wood species and derived empirical expressions for the prediction of ultimate direct withdrawal loads of single dowels from the end and side grains of those wood species as furniture structural members. In this study, the shear strength of dowel materials ranged from 15 to 18.5 MPa. The shear strength of test block materials ranged from 7 to 18.5 MPa. Specifically, 92% of tested connections were constructed with a dowel and test block with their total shear strength greater than 25 MPa, and only 8% of the tested connections were constructed with a dowel and test block with their total shear strength less than 25 MPa.

Eckelman (1979a, 1979b) conducted further study on the influence of the shear strengths (ranging from 7 to 16 MPa) of 15 wood species, which were commonly used for furniture frame structural member materials to the direct withdrawal load capacity. The dowel pin connections used sugar maple dowels with a high shear strength of 18 MPa. The results validated the use of two previously derived empirical expressions (Eckelman 1969), which can account for a wide range of shear strength values for wood members in predicting ultimate direct withdrawal loads of dowels in end and side grains of wood members when dowels are constructed of a high shear strength species like sugar maple.

However, limited literature has been found concerning the direct withdrawal load capacity of dowel connections constructed with dowel materials like yellow or white birch with low shear strengths of less than 12.0 MPa. Therefore, the primary objective of this study was to investigate the direct withdrawal load capacity of dowel connections mainly connected with dowels with a lower shear strength property. The specific objectives were to 1) study the effect of low shear strength property of dowel pin materials on ultimate direct withdrawal load of dowels in selected wood species as furniture frame structural members through comparing them with those dowels of wood species with high shear strength properties; 2) study the effect of shear strength property of selected wood species as furniture frame structural members on ultimate direct withdrawal load of evaluated dowels from those selected wood species for connection members; 3) study the effect of grain orientation of connection main members on ultimate direct withdrawal loads of evaluated dowels withdrawn from those main members of selected wood species; 4) evaluate the effects of dowel penetration depth in connection main members on ultimate direct withdrawal loads of dowels withdrawn from these main members; 5) evaluate the effect of dowel surface texture on ultimate direct withdrawal loads of dowels used in this study; 6) validate previously developed empirical expressions for predicting ultimate direct withdrawal loads of dowels in end and side grains of wood members. It is believed that the information found in this study could assist furniture manufacturers in their efforts of constructing an optimized design of their products and meanwhile lowering their material cost.

EXPERIMENTAL

Experimental Design

Dowel connections

A typical load block-to-test block single dowel connection in this study (Fig. 1a) consisted of a load block connected to a test block through a wooden dowel, and a piece of paper was included between the two blocks to prevent the load block end from adhering to the test block end or side. Test blocks for evaluating direct withdrawal loads of single dowels from their end and side grain orientations had a hole drilled in the center of one end of an end grain test block perpendicular to the face of that end (Fig. 1b) and the center of one narrow edge of a side gain test block perpendicular to the face of that edge (Fig. 1c). Load blocks had a hole drilled in the center of one end of a load block perpendicular to the face of that end (Fig. 1d).

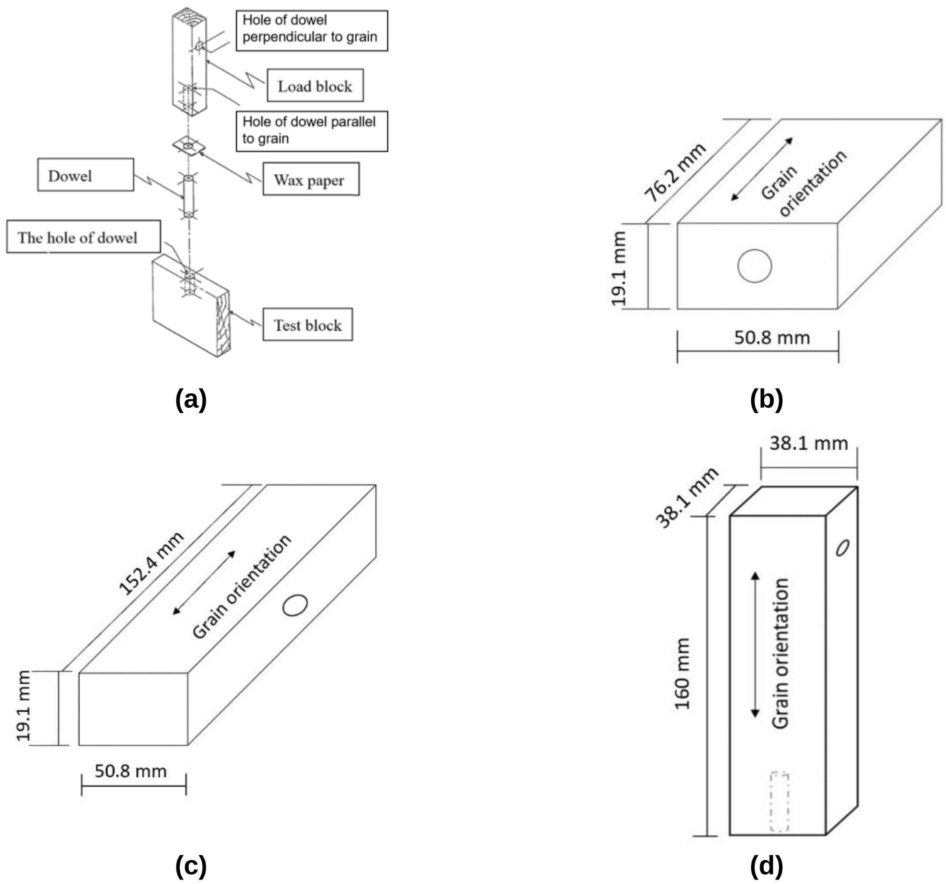
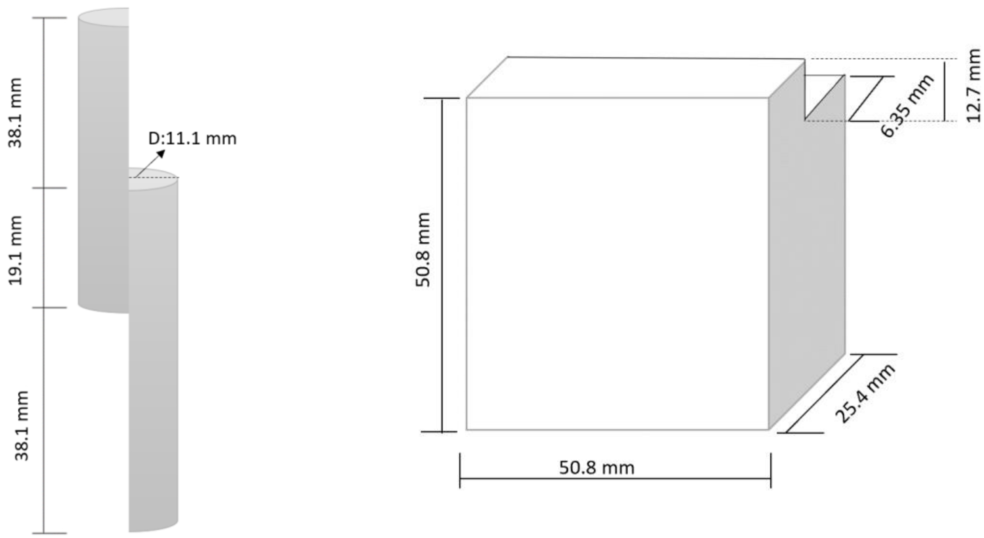


Fig. 1. Diagram showing a typical load block-to-test block single dowel connection (a) assembly for evaluating the ultimate direct withdrawal loads of single dowels from the end grain (b) and side grain (c) of a test block with a load block (d)

A complete 3 × 2 × 3 × 2 × 4 factor factorial experiment with 5 replications per combination was conducted to evaluate factors that influence ultimate direct withdrawal resistance loads of load block-to-test block single dowel connections. The five factors were wood species of test blocks (white oak, soft maple, and red oak) corresponding to different member shear strength, grain orientations of test blocks (side and end grain), wood species of dowels (yellow birch, white birch, and beech) indicating different dowel shear strength, wooden dowel type (spiral groove and multi-groove), and penetration depth of dowels in test blocks (12.7, 19.1, 25.4 and 38.1 mm). Therefore, a total of 720 withdrawal tests were performed.

Basic material properties

A complete one factor factorial experiment with 10 replications per combination was conducted to test the shear properties parallel to the wood grain orientation of the test block materials. The factor was the wood species of the test blocks (White oak/*Quercus alba*, Soft maple/*Acer rubrum*, and Red oak/*Quercus rubra*). Figure 2(a) shows the configuration and detailed dimensions of a shear test specimen for the test block materials. A complete one factor factorial experiment with 10 replications per combination was conducted to test the shear properties parallel to the wood grain orientation of the dowel materials. The factor was wood species of dowels (yellow birch/*Betula alleghaniensis*, White birch/*Betula*, and Beech/*Fagus*). Figure 2(b) shows the configuration and detailed dimensions of a shear test specimen for dowel materials. The specific gravity and moisture content of all tested materials were evaluated in accordance with ASTM F1575-03 (2013) and ASTM D5652-95 (2013) standards.



(a) **(b)**

Fig. 2. General configurations of shear strength tests for dowel (a) and test block materials (b)

Materials

Specimen preparation, and testing

Six test block supplies (*i.e.*, three wood species of white oak, soft maple, and red oak for each of the two grain orientation test blocks, end and side grain); and one load block supply (southern yellow pine) were provided by a local furniture manufacturer (East Mississippi Lumber Co., Aberdeen, MS, USA). Six supplies (*i.e.*, three wood species of yellow birch, white birch, and beech for each of the two dowel surface textures, spiral-groove and multi-groove) of machined dowels with a nominal diameter of 11.1 mm and length of 95.3 mm were supplied by Chicago Dowel Company (Chicago, IL, USA). A polyvinyl acetate emulsion adhesive with 60% solids content was provided by a commercial adhesives company (CNTs Ltd. Company, Tokyo, Japan).

All test blocks and dowels were conditioned in an equilibrium moisture content (MC) chamber controlled at 20 ± 2 °C and 50 ± 5% relative humidity prior to the drilling and assembly operations. All test blocks were randomly selected from their corresponding six supplies. Dowel holes were drilled with a standard twist drilling bit with its nominal diameter of 11.1 mm at a speed of 620 rpm. Minimum dowel-hole clearance was attempted. The holes in the test blocks were drilled 1.6 mm deeper than the required depth of dowel embedment to allow for variations in dowel lengths and adhesive escape. After the drilling operation, the diameters of drilled holes of 20 blocks selected from each combination of wood species by dowel surface texture were measured. The holes were drilled in load blocks for four penetration levels: 82.55, 76.2, 69.85, and 57.15 mm. Load block-to-test block single connection assembly began immediately after the dowel holes were drilled.

Cleanly machined dowels with no loose or torn surface fibers were randomly selected from each of the six common supplies, and the diameters of 20 selected dowels were measured. Both the maximum and the minimum diameter were recorded, and the measurements were averaged because dowels tend to be elliptical in their cross-section. Before assembly, the holes in the test blocks were cleaned with compressed air. Double gluing techniques were used in which both the walls of the holes and the sides of the dowels were liberally coated with glue prior to insertion of the dowels (Eckelman and Zhang 1993), *i.e.*, excess adhesive was used. The dowels were first inserted into the test blocks to ensure that the dowels were embedded to the required depth. During assembly, the samples were randomly selected to measure the depths of dowel embedment in the test blocks. All assembled load block-t-test block connections were stored in an equilibrium moisture content chamber controlled at 20 ± 2 °C and 50 ± 5% relative humidity for at least 1 week before testing. All dowel and test block material shear and connection direct withdrawal tests were completed on a hydraulic SATEC universal testing machine (Instron, Grove City, PA, USA). Figure 3 shows the setups for evaluating the shear strengths of dowel (a) and test block (b) materials.

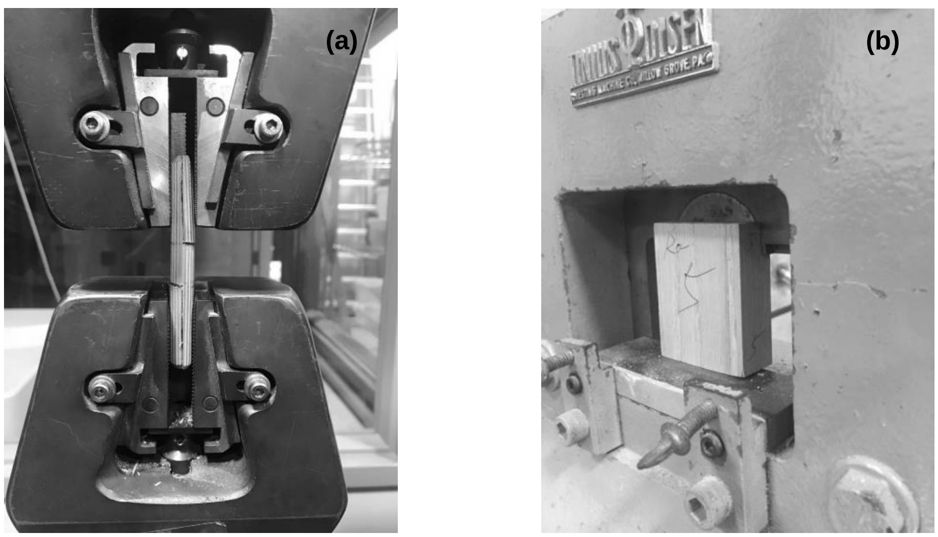


Fig. 3. Test setup for evaluating shear strength properties of dowel (a) and test block (b) materials

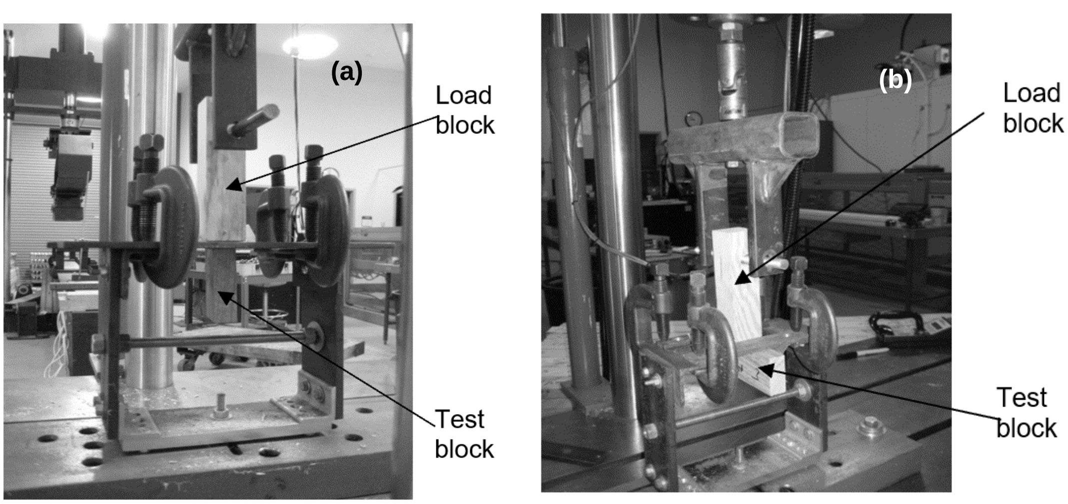


Fig. 4. Test setups for evaluating ultimate direct withdrawal loads of single dowels from the end grain of a test block (a) and the side grain of a test block (b)

Figure 4 shows the setups for evaluating ultimate direct withdrawal loads of single dowel from the end grain (a) and side grain (b) of a test block. The loading speed was 2.54 mm/min as per ASTM D5764-97 (2013). Ultimate withdrawal loads and failure modes of all tested connections were recorded.

RESULTS AND DISCUSSION

Basic Material Properties

Table 1 summarizes the mean values of the shear strength of the test block and dowel materials and their corresponding moisture content. The difference between the dowel hole in the test blocks and dowel diameters, *d*, averaged 0.08 mm.

Table 1. Physical and Mechanical Properties of Test Block and Dowel Materials

Properties	Connection Components					
	Test Block			Dowel		
	Wood Species					
	White Oak	Maple	Red Oak	Yellow Birch	White Birch	Beech
Moisture content (%)	8.4 (10.0)	8.2 (8.3)	8.5 (9.7)	8.6 (3.6)	8.3 (13.0)	8.2 (7.1)
Shear strength (MPa)	11.0 (15.1)	8.7 (11.4)	11.9 (10.5)	9.3 (29.9)	12.0 (27.4)	20.8 (18.9)

[a] Values in parentheses are coefficients of variation in percentage

Dowel Connections

Failure modes

There were three typical failure modes that occurred in this study, as shown in Fig. 5. Type I was dowels sheared parallel-to-the-grain. Type I failure mode mostly happened in tests with dowel shear strength equal to or less than 12.0 MPa. Type II was the dowel's withdrawal from test blocks with some wood pieces off from test blocks attached to the dowels. Type II failure mode mostly occurred in the tests of end blocks with its shear strength at 8.7 MPa. Type III was a dowel surface shear. Type III failure mode was mostly observed in the tests with dowel shear strength equal to 20.8 MPa.

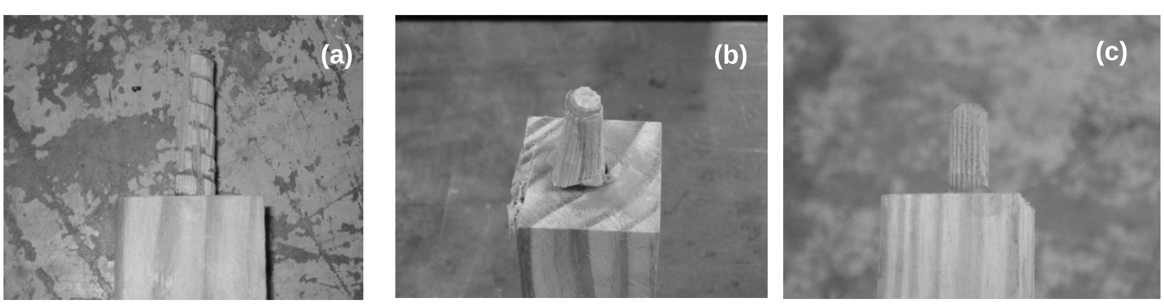


Fig. 5. Typical failure modes observed in dowel withdrawal tests: (a) dowels sheared parallel-to the-grain, (b) dowel's withdrawal from test blocks with some wood pieces attached to the dowels, and (c) dowel surface shear

Mean comparison of ultimate loads

Table 2 summarizes the mean values of ultimate withdrawal loads of tested connections. In general, the mean ultimate withdrawal load of single dowels withdrawn from wood species evaluated in this study ranged from 1864 to 8260 N with their corresponding coefficients of variation (COV) ranging from 5 to 42%.

Table 2. Mean Values of Ultimate Direct Withdrawal Resistance Loads of Single Dowels from Test Blocks Evaluated in this Study

Shear Strength		Dowel Surface Texture	Penetration Depth	Grain Orientation	
Test Block	Dowel			End Grain	Side Grain
(MPa)			(mm)	(N)	
8.7	9.3	Spiral-groove	12.7	3043 (30)	3785 (16)
8.7	9.3	Spiral-groove	19.1	5752 (13)	4413 (16)
8.7	9.3	Spiral-groove	25.4	5738 (20)	6374 (6)
8.7	9.3	Spiral-groove	38.1	6263 (12)	8118 (15)
8.7	9.3	Multi-groove	12.7	3781 (30)	3105 (19)
8.7	9.3	Multi-groove	19.1	5018 (20)	4119 (14)
8.7	9.3	Multi-groove	25.4	6281 (30)	5436 (17)
8.7	9.3	Multi-groove	38.1	6712 (23)	7482 (11)
8.7	12.0	Spiral-groove	12.7	3203 (23)	3167 (13)
8.7	12.0	Spiral-groove	19.1	4564 (14)	4702 (18)
8.7	12.0	Spiral-groove	25.4	4417 (11)	6508 (10)
8.7	12.0	Spiral-groove	38.1	7940 (13)	7775(15)
8.7	12.0	Multi-grove	12.7	3474 (20)	2758 (17)
8.7	12.0	Multi-grove	19.1	4235 (22)	4381 (23)
8.7	12.0	Multi-grove	25.4	4599 (25)	6112 (6)
8.7	12.0	Multi-grove	38.1	6116 (20)	8162 (10)
8.7	20.8	Spiral-grove	12.7	3545 (23)	3585 (13)
8.7	20.8	Spiral-grove	19.1	4902 (13)	4897 (15)
8.7	20.8	Spiral-grove	25.4	5378 (9)	6272 (14)
8.7	20.8	Spiral-grove	38.1	7411 (20)	7807 (13)
8.7	20.8	Multi-grove	12.7	3398 (15)	3874 (12)
8.7	20.8	Multi-grove	19.1	5049 (9)	4350 (14)
8.7	20.8	Multi-grove	25.4	5587 (14)	6725 (14)
8.7	20.8	Multi-grove	38.1	8278 (5)	7727 (5)
11.0	9.3	Spiral-grove	12.7	4057 (16)	3550 (18)
11.0	9.3	Spiral-grove	19.1	5382 (8)	4453 (19)
11.0	9.3	Spiral-grove	25.4	6859 (14)	5084 (12)
11.0	9.3	Spiral-grove	38.1	6170 (18)	6677 (23)
11.0	9.3	Multi-grove	12.7	5138 (22)	3203 (12)
11.0	9.3	Multi-grove	19.1	6779 (15)	4862 (15)
11.0	9.3	Multi-grove	25.4	6623 (23)	5809 (6)
11.0	9.3	Multi-grove	38.1	7980 (13)	5409 (25)
11.0	12.0	Spiral-grove	12.7	3670 (29)	3496 (19)
11.0	12.0	Spiral-grove	19.1	4853 (25)	3705 (14)

11.0	12.0	Spiral-grove	25.4	6143 (14)	5934 (25)
11.0	12.0	Spiral-grove	38.1	5440 (6)	7063 (7)
11.0	12.0	Multi-grove	12.7	4457 (15)	3398 (14)
11.0	12.0	Multi-grove	19.1	3496 (16)	4915 (6)
11.0	12.0	Multi-grove	25.4	6325 (24)	5654 (6)
11.0	12.0	Multi-grove	38.1	6707 (23)	7024 (28)
11.0	20.8	Spiral-grove	12.7	3541 (23)	3590 (14)
11.0	20.8	Spiral-grove	19.1	5943 (12)	5013 (12)
11.0	20.8	Spiral-grove	25.4	5792 (16)	5035 (25)
11.0	20.8	Spiral-grove	38.1	8563(12)	7878 (16)
11.0	20.8	Multi-grove	12.7	3652 (23)	3114 (15)
11.0	20.8	Multi-grove	19.1	6512 (20)	4123 (21)
11.0	20.8	Multi-grove	25.4	6766 (17)	5534 (31)
11.0	20.8	Multi-grove	38.1	7936 (20)	7535 (18)
11.9	9.3	Spiral grove	12.7	3016 (21)	3064 (7)
11.9	9.3	Spiral-grove	19.1	4141 (19)	5000 (7)
11.9	9.3	Spiral-grove	25.4	5040 (32)	6014 (21)
11.9	9.3	Spiral-grove	38.1	6134 (22)	7744 (25)
11.9	9.3	Multi-grove	12.7	2949 (31)	3136(10)
11.9	9.3	Multi-grove	19.1	4208 (34)	4181 (21)
11.9	9.3	Multi-grove	25.4	5062 (42)	6156 (21)
11.9	9.3	Multi-grove	38.1	7629 (15)	6210 (22)
11.9	12.0	Spiral-grove	12.7	1864 (22)	2931 (12)
11.9	12.0	Spiral-grove	19.1	4097 (18)	4488 (17)
11.9	12.0	Spiral-grove	25.4	4973 (15)	6365 (17)
11.9	12.0	Spiral-grove	38.1	4644 (38)	7224 (12)
11.9	12.0	Multi-grove	12.7	3096 (39)	3020 (9)
11.9	12.0	Multi-grove	19.1	3830 (15)	4346 (23)
11.9	12.0	Multi-grove	25.4	5827 (12)	6615 (8)
11.9	12.0	Multi-grove	38.1	6557 (17)	7802 (8)
11.9	20.8	Spiral-grove	12.7	2740 (24)	2980 (22)
11.9	20.8	Spiral-grove	19.1	5098 (8)	3421 (9)
11.9	20.8	Spiral-grove	25.4	5618 (9)	6392 (18)
11.9	20.8	Spiral-grove	38.1	6517(20)	8260 (9)
11.9	20.8	Multi-grove	12.7	2709 (28)	2860 (11)
11.9	20.8	Multi-grove	19.1	4635 (28)	5560 (10)
11.9	20.8	Multi-grove	25.4	5921 (15)	7326 (2)
11.9	20.8	Multi-grove	38.1	5934 (16)	6526 (34)

[a] Value in parentheses are coefficients of variation in percentage

A five-factor analysis of variance (ANOVA) general linear model (GLM) procedure was performed at the 5% significance level to analyze the five main effects and their interactions on ultimate direct withdrawal loads of single dowels from tested blocks. The ANOVA results (Table 3) indicated that the five-way interaction was significant. This suggested that further analyses should be focused on the significant interaction. The protected least significant difference (LSD) multiple comparisons procedure was used to compare the mean differences among 144 treatment combinations, *i.e.*, mean comparisons among these combinations were performed using a single LSD value of 1210 N derived using a one-way classification with 144 treatment combinations with respect to the five-factor interaction. The outputs were provided by SAS software 2014 (SAS Institute Inc., Cary, NC, USA).

Table 3. Summary of ANOVA Results Obtained from the GLM Procedure Performed on Five Factors for Ultimate Direct Withdrawal Loads

Source	df	F value	p value
Block-shear strength	2	12.17	< 0.0001
Grain Orientation of Test Block	1	1.54	0.2153
Dowel-shear strength	2	11.65	< 0.0001
Texture of dowel type	1	1.20	0.2728
Penetration depth	3	489.58	< 0.0001
Block-shear × orientation × dowel-shear × texture × penetration	12	2.01	0.0213

Mean comparisons of ultimate withdrawal loads of single dowels for the shear strength of dowel materials indicated that there was no significant increasing trend in the ultimate direct withdrawal load of single dowels from the evaluated three wood species as the dowel shear strength increased from 9.3 to 20.8 MPa. For instance, when a spiral groove dowel was inserted into a test block of a shear strength of 8.7 MPa at a penetration depth of 19.1 mm, the mean values of ultimate direct withdrawal load were 5752, 4564, and 4902 N for dowel strengths of 9.3, 12, and 20.8 MPa, respectively (Table 2), *i.e.*, there was no significant difference among these three mean values based on the LSD value of 1210 N because the difference between any set of two means was less than 1210 N. This implies that a minimum shear strength value of 9.3 MPa should be sufficient for a wood species considered as a dowel material.

Mean comparisons of ultimate withdrawal loads of single dowels for the shear strength of test block materials indicated that there was no significant increasing trend in the ultimate direct withdrawal load of single dowels as the shear strength of test block materials increased from 8.7 to 11.9 MPa. For instance, the mean values of ultimate withdrawal loads were 5752, 4564, and 4902 N for test blocks of shear strengths of 8.7, 11, and 11.9 MPa, respectively, when spiral groove dowels of shear strength of 9.3 MPa were inserted into these test blocks with a penetration depth of 38.1 mm (Table 2), *i.e.*, there was no significant difference among these three mean values based on the LSD value of 1210 N. This implies that a minimum shear strength value of 8.7 MPa of a wood material as a furniture member can be sufficient to reach the limit of a withdrawal load of a dowel withdrawn from the member.

Mean comparisons of ultimate direct withdrawal loads of single dowels for dowel surface texture indicated that 12 mean differences were observed between spiral and multi-groove dowels among all means of 72 treatment combinations of test block material shear strength by dowel material shear strength by test block grain orientation by dowel penetration depth. The mean values of ultimate withdrawal loads were 3545 N, 3585 N, 3398 N, and 3874 N for different end and side grain, while test blocks of shear strength of 8.7 MPa and dowel shear strength of 20.8 MPa at 12.7 mm, there was no significant difference among their mean values based on the LSD value of 1210 N. This could imply that in general there is no significant difference in ultimate direct withdrawal loads between spiral and multi-groove dowels (Eckelman and Hill 1971).

Mean comparisons of ultimate withdrawal loads of single dowels for test block grain orientation conditions indicated that among all means of 72 treatment combinations of test block material shear strength by dowel material shear strength by dowel surface texture by dowel penetration depth, there were no significant differences in ultimate withdrawal loads between end and side grain orientation of 52 pairs, but 20 mean differences were observed between end and side orientations. Among these two means, there were seven pairs in 38.1 mm penetration depth and four pairs in 25.4 mm penetration depth, one pair in 19.1 penetration depth, where end grain had significant higher mean ultimate direct withdrawal loads than side one, and there were one pair in 38.1 mm, two pairs in 25.4 mm, four pairs in 19.1 mm, and one pair in 12.7 mm, where side grain had significant higher mean ultimate withdrawal loads than end one. This indicated that among the differences end grain tended to have higher ultimate withdrawal loads.

Mean comparisons of ultimate withdrawal loads of single dowels for dowel penetration depth indicated that in general the mean ultimate direct withdrawal loads of single dowels increased as the dowel penetration increased from 12.7 to 38.1 mm, *i.e.*, the mean values of ultimate withdrawal loads at different penetration depth were 3167 N, 4702 N, 6508 N, and 7775 N for test block shear strength of 8.7 MPa and dowel shear strength of 12.0 MPa with spiral-grove dowel surface texture at side grain type based on the LSD value of 1210 N, but significances were affected by the conditions of different treatment combinations of test block material shear strength by dowel material shear strength by test block grain orientation by dowel surface texture.

Prediction on ultimate direct withdrawal loads

The following Eqs. 1 and 2 developed by Eckelman (1969) were first used to estimate ultimate direct withdrawal loads of single dowels from the end, F_{end} (N), and side, F_{side} (N), grains of test blocks, respectively,

$$F_{\mathrm{end}} = 0.834 \times D \times L^{0.89} (S_1 + S_2) \times a \times b \times c \quad (1)$$

$$F_{\mathrm{side}} = 0.834 \times D \times L^{0.89} (0.95S_1 + S_2) \times a \times b \times c \quad (2)$$

where D is the dowel diameter (mm), L is the dowel penetration depth in the wood member (mm), S_1 and S_2 are the shear strength parallel-to-the-grain for the connection member and dowel materials, respectively (MPa), a is the correction factor for gap-filling adhesive, *i.e.*, 0.9 for polyvinyl adhesives with less than 60% solid content, b is the correction factor for dowel-hole clearance, *i.e.*, 1.0 - (17.1d) for polyvinyl acetates adhesive, d is the difference between the dowel hole and dowel diameters, and c is the correction factor for dowel surface texture, *i.e.*, 0.9 for spiral-groove and multi-groove dowels.

Figure 6 plots the estimated mean values of ultimate direct withdrawal loads of single dowels withdrawn from end grain of test blocks using Eq. 1 *versus* material shear property (S_1 + S_2) along with their corresponding mean values of experimental data points. In general, all plots indicate that the estimation expression tends to significantly underestimate the mean values of ultimate direct withdrawal loads of single dowels from the end grain of test blocks when the material shear property was less than 25 MPa. Specifically, the ratio of estimated load to test load were in the range from 0.62 to 0.87. The experimental data points of mean ultimate direct withdrawal loads of dowels with the material shear property greater than 30 MPa fit the estimated line reasonably well, *i.e.*, the ratio of estimated load to test load was in the range 0.98 to 1.15.

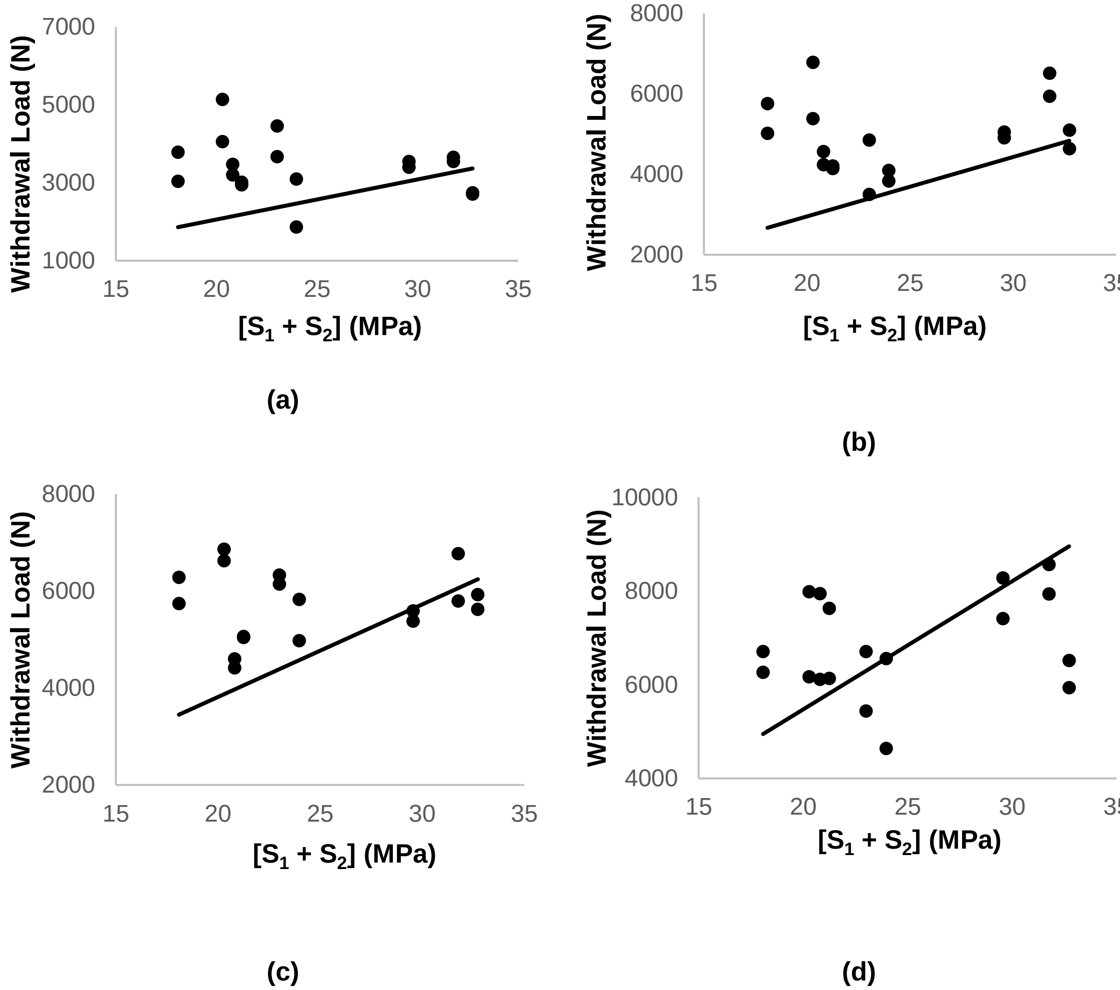


Fig. 6. Plots showing the estimated line along with experimental data points of mean values of ultimate direct withdrawal loads of single dowels from the end grain of test blocks *versus* material shear property (S_1 + S_2) for each of the four dowel penetration depths: 12.7 (a), 19.1 (b), 25.4 (c), and 38.1 mm (d), respectively

Figure 7 plots the estimated mean values of ultimate direct withdrawal loads of single dowels withdrawn from the side grain of test blocks as a function of material shear property (0.95 S_1 + S_2) together with individual experimental data points. In general, all plots indicate that the estimation expression tended to significantly underestimate the mean values of ultimate direct withdrawal loads of single dowels from the side grain of test blocks when the material shear property was less than 25 MPa. Specifically, the ratio of estimated load to test load was in the range from 0.66 to 0.78. The experimental data points of mean ultimate direct withdrawal loads of dowels with the material shear property greater than 30 MPa fit the estimated line reasonably well, *i.e.*, the ratio of estimated load to test load was in the range from 0.95 to 1.11.

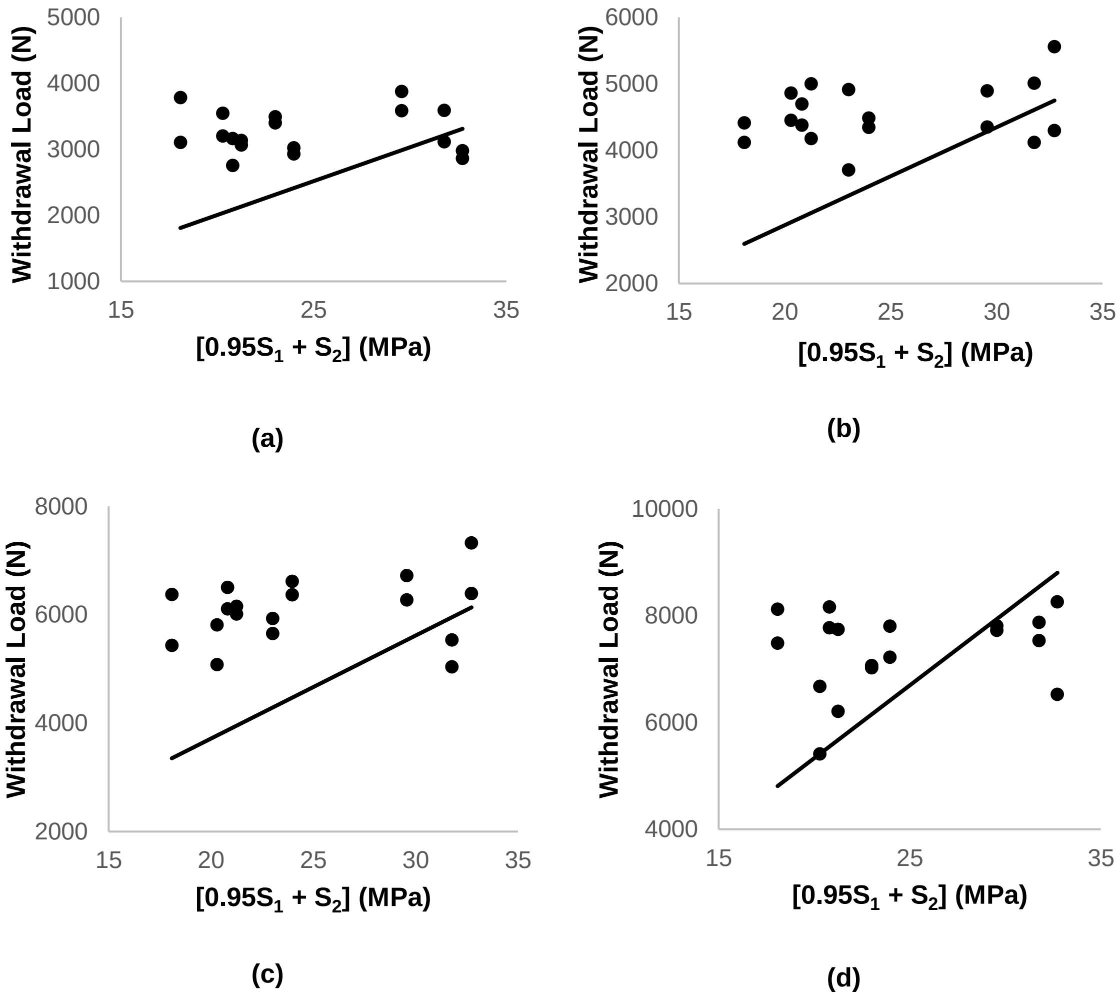


Fig. 7. Plots showing the estimated line along with experimental data points of mean values of ultimate direct withdrawal loads of single dowels from the side grain of test blocks *versus* material shear property ($0.95S_1 + S_2$) for each of the four dowel penetration depths: 12.7 (a), 19.1 (b), 25.4 (c), and 38.1 mm (d), respectively

The following Eqs. 3 and 4 were proposed to fit individual experimental data points of test values with lower shear property of less than 25 MPa, considering of dowel penetration depth as a major consideration of contributing the higher ultimate direct withdrawal loads:

$$F_{\mathrm{end}} = 0.834 \times D \times L^{\alpha} (S_1 + S_2) \times a \times b \times c \tag{3}$$

$$F_{\mathrm{side}} = 0.834 \times D \times L^{\beta} (0.95 \times S_1 + S_2) \times a \times b \times c \tag{4}$$

The rationale of this consideration is that the lower shear property of tested dowels and blocks yielded higher ultimate direct withdrawal loads because of more dowel and test block materials participating to resist the withdrawal load, *i.e.*, dowel and test block materials tended to break with the failure modes I and II (Fig. 5) of dowel or test block shear failure. The regression analyses resulted in the values of 1.00 and 0.99 for the regression constants' α and β values, respectively. The corresponding values of coefficient of determination, r^2, were 0.962 and 0.945, respectively. Compared to Eqs. 1 and 2, these increases in power of dowel penetration depth reflect the dowel or test block materials involvement.

CONCLUSIONS

1. Connections using dowels and main members with low shear strength properties can achieve the same ultimate direct withdrawal loads as connections using the materials with higher shear strength properties for dowels and main members.
2. The existing empirical equations, including shear strength properties for both dowel and main member materials, used to construct dowel connections tend to significantly underestimate ultimate direct withdrawal loads of the evaluated dowel connections withdrawn from end and side grains of tested wood species, as the connection main members in this study when these two shear strength values were added together were less than 25 MPa. Both estimation expressions were modified to consider the lower shear strength effort on ultimate direct withdrawal loads of dowels evaluated in this experiment.
3. Increasing shear strength properties of both dowel and test block materials will not significantly increase ultimate direct withdrawal loads of dowels from evaluated wood species as test blocks in this experiment.
4. The grain orientation of connection member materials as test blocks in this study had significant influence on the ultimate direct withdrawal loads of dowels withdrawn from these evaluated wood species.
5. Mean values of ultimate direct withdrawal loads of dowels from evaluated wood species as test blocks in this experiment increased significantly as dowel penetration depth in test blocks increased from 12.7 to 38.1 mm at increments of 6.35 mm.
6. Dowel surface texture had no significant effect on ultimate direct withdrawal loads of dowels from evaluated wood species as test blocks in this experiment.

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