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ORIGINAL ARTICLE

Influence of welded depth and $CuCl_2$ pretreated dowels on wood dowel welding

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Abstract This study examined the influence of welded depth and $CuCl_2$ pretreated dowels on wood dowel welding. In untreated group without pretreatment (group A), test results indicated that welded depth 40 mm exhibited higher pullout resistance than the other welded depths. In the same welded depth of 30 mm, specimens with dowels immersed in $CuCl_2$ solution for 30 min (group B) exhibited the highest pullout resistance than the other specimens. According to the failure behavior, the pullout resistance of group B was considered to be the maximum theory pullout resistance in the welded depth of 30 mm. Weibull distribution could be applied reasonably to analyze pullout resistance of different welded depth. The linear simulation and Eckelman formula could not fit the relation of pullout resistance and welded depth. While the nonlinear simulation of sine function could fit the relation accurately. Based on the Weibull distribution, 95% reliability pullout resistance was calculated. The nonlinear simulation of sine function also existed between 95% reliability pullout resistance and welded depth. The temperature difference of group A-30 and group B was tested to study the reason of different pullout resistance. Both of the two groups, the temperature of point 1 was the highest, and the point 3 was the lowest. The pullout resistance was affected significantly by the temperature of point 2 and 3. For point 1, 260 °C was an excessive temperature, while 224.3 °C was the better choice for welding in this study.

Keywords Welded depth · Pretreated dowels · Weibull distribution · Regression analyses · Welding temperature

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Introduction

Wood dowel welding is an environmentally friendly technology of connecting wood to create a new welding interface layer with the production of friction heating. During the welding process, the properties of welded joints could be influenced by rotation speed, insertion speed, moisture content, welded depth, and pretreatment [1].

Several researchers studied the influence of rotation speed and moisture content on the welded joints. The best pullout resistance was obtained in the rotation speed range of 1200–1600 rpm [2]. Later, Rodriguez found that the welded joints with rotation speed of 1000 and 1500 rpm showed similar pullout resistance [3]. Chedeville also indicated that no significant variance existed between pullout resistance and rotation speed in the range of 1165–1515 rpm. While it was found that significant variance existed between pullout resistance and moisture content (MC) of wood dowel [4]. Furthermore, Kanazawa found that wood dowels with 1% MC could improve the pullout resistance by 57.66% than untreated specimens, because dry dowels could inflate after absorbing water from the environment [5]. Pizzi also chose wood dowels with 2% MC in his study [6].

On the other hand, welded depth was an important factor to the welded joints. According to J. M. Leban, the pullout resistance of weld joints could reach a maximum of 2145 N at a weld-depth of 22 mm, while 2500–2500 N could get at a weld-depth of 46 mm [2]. Kanazawa studied the pullout resistance of welded depths 15 and 30 mm. The test result showed that pullout resistance of 30 mm was twice larger than that of 15 mm [5]. So the welded depth of 20–30 mm was frequently used in the other studies [7, 8]. But few researches focused on the regression relation between pullout resistance and welded depth.

The pretreatment methods of wood dowels were analyzed. Wood dowels soaked in ethylene glycol for 10 min could improve the pullout resistance by 98.05% [5]. Similar conclusion was obtained from Chedeville [4]. The interactions rotation rate/ethylene glycol were the second most significant in wood dowel welding. While the treatment with sunflower oil and water reduced the pullout resistance [5]. Amirous also found that citric acid was used as waterproofing additive in butt joints linear wood welding [9]. And in our previous study, wood dowel with diameter of 12 mm pretreated in 0.1 mol/L $CuCl_2$ acid solution with immersion time of 1, 3, 5, and 7 days were studied. So it was necessary to analyze the influence of shorter immersion time on wood dowel with the diameter of 10 mm and the pullout resistance. Meanwhile, the influence of pretreatment on temperature of welding interface should be studied.

The highest temperature of welding interface was studied by several researchers. According to the equation of Zoulalian, a temperature of 180 °C was optimal for beech during rotational dowel welding [10]. But other studies found that the temperature was affected by species, rotational rate and other parameters. At the very beginning of welding, the tip of dowels reached a temperature higher than 45 °C. The temperature increased from 20 to 183 °C during the 7 s of welding [5]. With optimal parameters, peak welding temperatures of 244 and 282 °C for sugar maple and yellow birch were tested by thermocouples, respectively [11]. They studied the highest temperature of the welding interface, but few researches indicated the difference of the temperature at different depth position in one welding interface.

According to previous studies, several parameters were set in this study; Rotation speed was 1080 rpm and The MC of wood dowels was 2%. This study aimed to find the linear and nonlinear regression relation between the pullout resistance and welded depth. Meanwhile, the nonlinear regression analyses between welded depth and 95% reliability pullout resistance which was calculated by Weibull distribution was studied. Based on the regression relation, appropriate welded depth should be applied in the practical engineering. And then the influence of pretreatment with immersion in $CuCl_2$ solution on the temperature of welding interface was studied to indicate the difference of pullout resistance between treated and untreated specimens.

Materials and methods

Materials

Wood dowels were made of birch (*Betula*), and were 10 mm in diameter and 100 mm in length. Dowels were pre-conditioned at 63 °C to obtain a 2% moisture content. Wood dowels with a 2% moisture content were divided into two categories including an untreated group without pretreatment (group A) and two pretreatment groups (groups B and C). Wood dowels of group B and C were immersed in 0.1 mol/L $CuCl_2$ for 30 min and 7 days, respectively. Then wood dowels were dried to 2% moisture content for wood dowel welding. The tensile properties of untreated and treated wood dowels are shown in Table 1. According to the different welded depth, group A was divided into group A-10—group A-50 (Table 2).

Larch (*Larix*) slats, that were 40 mm (tangential, *T*) × 50 mm (radial, *R*) × 500 mm (longitudinal, *L*) were used as the substrate. Slats were pre-conditioned at 20 °C and 60% relative humidity (RH), until equilibrium moisture content was achieved.

Manufacturer of specimen

Wood substrates were pre-drilled with holes 8 mm in diameter using a drilling machine (Proxxon TBH Typ 28 124). Next, the wood dowels were welded into the pre-drilled holes in the substrates to create bonded joints with a high-speed rotation at 1080 rpm [2]. The insert part of the dowel was transferred to a conical shape because of the

Table 1 Tensile properties of untreated and treated wood dowels

Group	Group A	Group B	Group C
Tensile strength (N)	4864	4791	1064

Group A meant the untreated wood dowels

Group B meant the treated group with wood dowels immersed in $CuCl_2$ for 30 min

Group C meant the treated group with wood dowels immersed in $CuCl_2$ for 7 days

Table 2 Results of the pullout resistance of different welded depth

Group	Welded depth (mm)	Maximum value (N)	Minimum value (N)	Mean value (N)	Standard deviation	Variable coefficient (%)
A-10	10	1358	498	854	233	27.28
A-20	20	1684	738	1140	280	24.56
A-30	30	2290	1536	1857	228	12.28
A-40	40	2966	1800	2317	304	13.12
A-50	50	2538	1672	2126	311	14.63

Group A-10 meant the untreated group, and the number 10 meant the welded depth 10 mm

different abrasion level during the welding process. The rotation of the wood dowel stopped when the fusion and bonding was achieved in approximately 4 s [11]. After welding, wood slats were cut into 10 parts evenly in the length direction so that every welded dowel was 40 mm (*T*) × 50 mm (*R*) × 50 mm (*L*) in size. The specimens were conditioned at 20 °C and 60% RH for 7 days before the tests were conducted.

Pullout test

The pullout resistance of the specimens was tested using universal testing equipment (WDW-300E) that pulled the welding wood dowels out of the substrate at a speed of 2 mm/min [12]. The specimens were fixed by clamping the dowel into the jaw of the fixed beam and the substrate block was fixed to the mobile beam with a metal framework.

Weibull distribution

95% reliability value calculated by Weibull distribution was widely used in practical engineering application. The Weibull distribution function was $F(x) = 1 - \exp\left[-\left(\frac{x-a_0}{\beta}\right)^{\alpha}\right]$, and the probability density function was $f(x) = \frac{\alpha}{\beta}\left(\frac{x-a_0}{\beta}\right)^{\alpha-1}\exp\left[-\left(\frac{x-a_0}{\beta}\right)^{\alpha}\right]$. α, β, and a_0 were the shape parameter, scale parameter and location parameter [13, 14], respectively.

The parameters of Weibull distribution were calculated by least square method [15]. Based on the calculated parameters, the cumulative distribution function and probability density function were set. And then the 95% reliability value could be calculated to evaluate the reliability of the materials.

Temperature test

Temperature was tested using three thermocouple sensors with the data collecting device (XSL-A16XS1V0). Three sensors were set in three different depths (Fig. 1). The response speed of the thermocouple sensor was 0.34 ms [11].

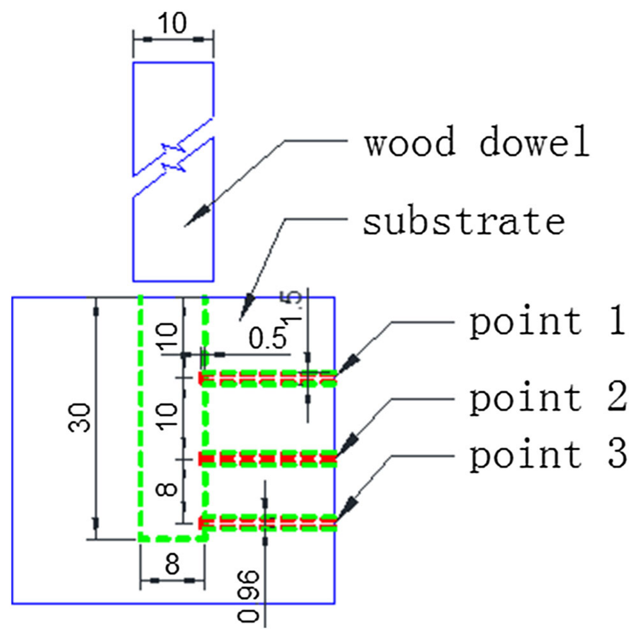

Fig. 1 The distribution of temperature test points

Results and discussion

Surface morphology of the welding interface

Twenty replicate welding specimens were tested for each group. The pullout resistance results of different welded depth are summarized in Table 2. The pullout resistance results of different pretreated methods are summarized in Table 3. The mean values of the different welded depth using untreated wood dowels are shown in Fig. 2. Group A-40 showed the best pullout resistance. The pullout resistance of group A-40 was 24.77 and 8.98% higher than group A-30 and A-50, respectively. The surface morphology of each group is shown in Fig. 3. The welded depth 10 mm indicated excellent welded joints because the rupture occurred in wood dowel instead of welding interface (Fig. 3a). On the other hand, for welded depth 20 mm, few molten black materials existed at the tip of the wood dowel (Fig. 3b). The same phenomenon could be found in welded depth 30 mm. 3 mm at the tip of the wood dowel was lack of molten black materials (Fig. 3c). And then for 40 and 50 mm welded

Table 3 Results of the pullout resistance of 30 mm welded depth for different pretreated methods

Group	Maximum value (N)	Minimum value (N)	Mean value (N)	Standard deviation	Variable coefficient (%)
Group A-30	2290	1536	1857	228	12.28
Group B	6094	3006	4697	872	18.57
Group C	1400	404	924	275	29.76

Group A-30 meant the untreated group, and the number 30 meant the welded depth 30 mm

Group B meant the treated group with wood dowels immersed in $CuCl_2$ for 30 min

Group C meant the treated group with wood dowels immersed in $CuCl_2$ for 7 days

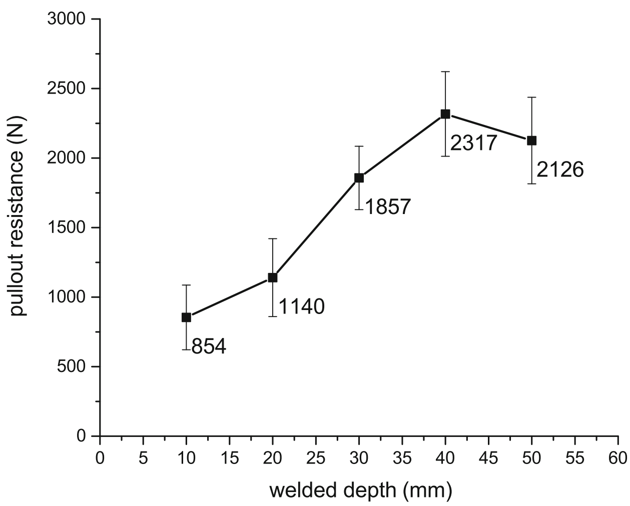

Fig. 2 The pullout resistance of different welded depth

depths, they were difficult to operate. The dowels were easy to fracture during the welding process, because of the excessive torque. Furthermore, the phenomena of lack of molten black materials were found in their welding interface, especially for welded depth 50 mm (Fig. 3d, e). So in the study of pretreated methods, the welded depth was 30 mm. The pullout resistance of group B was 152.93% higher than group A-30. While the pullout resistance of group C was 50.24%, lower than group A-30. Figure 3f, g were the typical failure modes with the shear fracture of wood dowels for group B after pullout tests. While for group C, the wood dowel welded into substrate was serious deformation to tapered tip during the welding process (Fig. 3h). According to this phenomenon, the pullout resistance could be improved obviously by immersing the dowels into $CuCl_2$ solution for appropriate time.

Weibull distribution of pullout resistance for different welded depth

All the specimens were broken with brittle rupture during the pullout tests. So in this study, $a_0 = 0$ was assumed. Because there was discontinuity of the welding interface, and pullout resistance with 0 N was reasonable. The Weibull distribution function should be rewritten as

$$1 - F(x) = \exp\left[-\left(\frac{x}{\beta}\right)^{\alpha}\right] \tag{1}$$

Both sides were taken logarithm, Eq. 1 could be turned to

$$\ln[-\ln(1 - F(x))] = \alpha \ln x - \alpha \ln \beta \tag{2}$$

In the Weibull distribution probability graph, $\ln x$ and $\ln\,[-\ln\,(1 - F(x))]$ were set to X-coordinate and Y-coordinate, respectively. So Eq. 2 could be rewritten to linear Eq. 3. In this formula, $b = \alpha$ and $a = -\alpha \ln \beta$ were considered [16, 17].

$$Y = bX + a \tag{3}$$

For the four welded groups, four equations could be set, respectively.

$$Y = 3.7782X - 0.2143 \quad \text{(group A-10)} \tag{4}$$

$$Y = 4.3397X - 0.9668 \quad \text{(group A-20)} \tag{5}$$

$$Y = 8.5448X - 5.7489 \quad \text{(group A-30)} \tag{6}$$

$$Y = 7.9701X - 7.1523 \quad \text{(group A-40)} \tag{7}$$

$$Y = 6.5786X - 5.3957 \quad \text{(group A-50)} \tag{8}$$

Based on Eqs. 4–8, the parameters α and β were calculated in the Table 4. And then the formulas of cumulative distribution and probability density distribution for each group are shown below (Eqs. 9–18). The graphs of them are shown in Figs. 4 and 5.

Group A-10:

$$F(x) = 1 - \exp\left[-\left(\frac{x}{1.0584}\right)^{3.7782}\right] \tag{9}$$

$$f(x) = 3.56973 \times \left(\frac{x}{1.0584}\right)^{2.7782} \times \exp\left[-\left(\frac{x}{1.0584}\right)^{3.7782}\right] \tag{10}$$

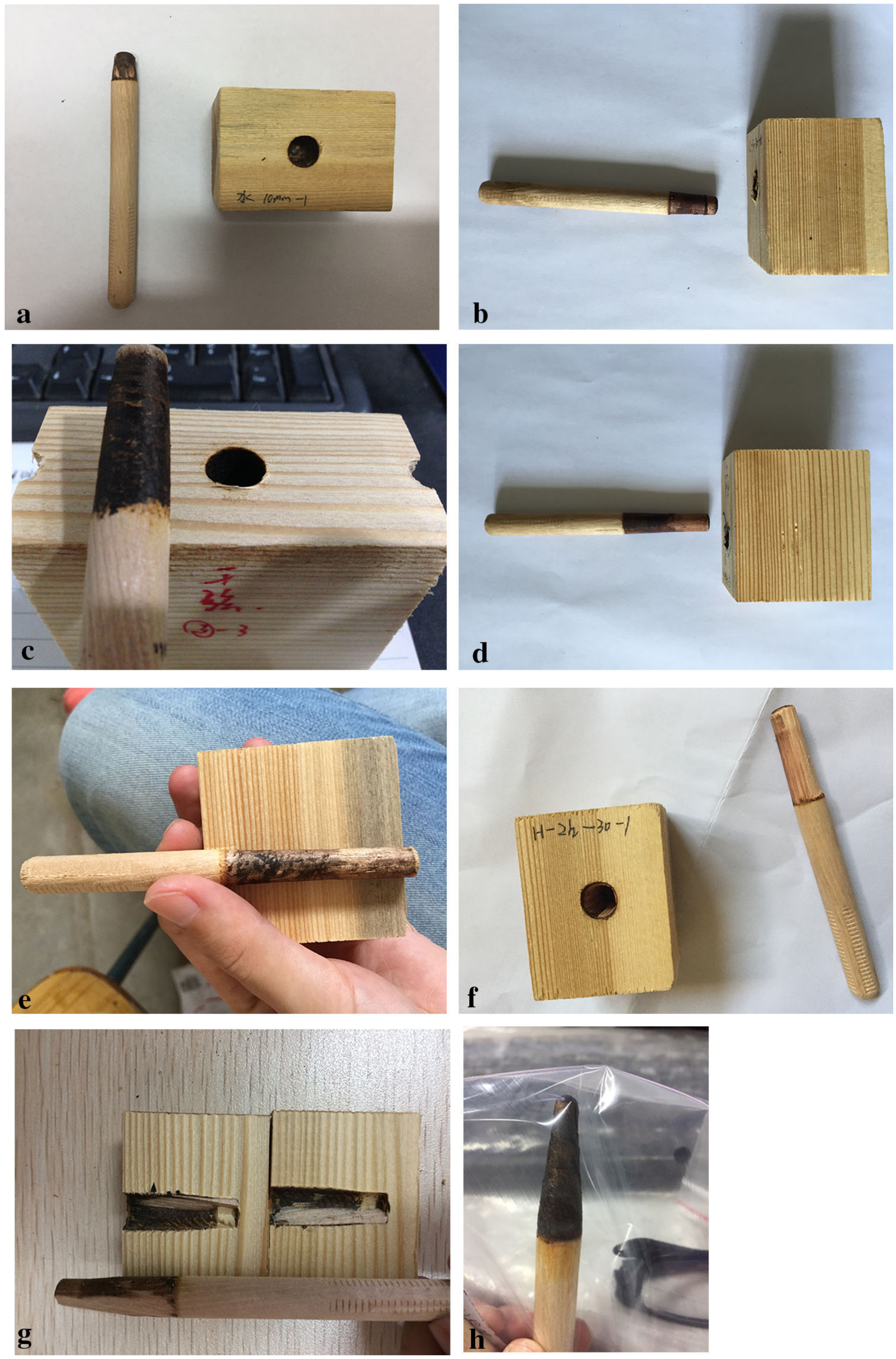

Fig. 3 The surface morphology of each group

Table 4 The parameters of Weibull distribution for different welded depth

Parameters of Weibull distribution	10 mm	20 mm	30 mm	40 mm	50 mm
α	3.7782	4.3397	8.5448	7.9701	6.5786
β	1.0584	1.2496	1.9597	2.4532	2.2709

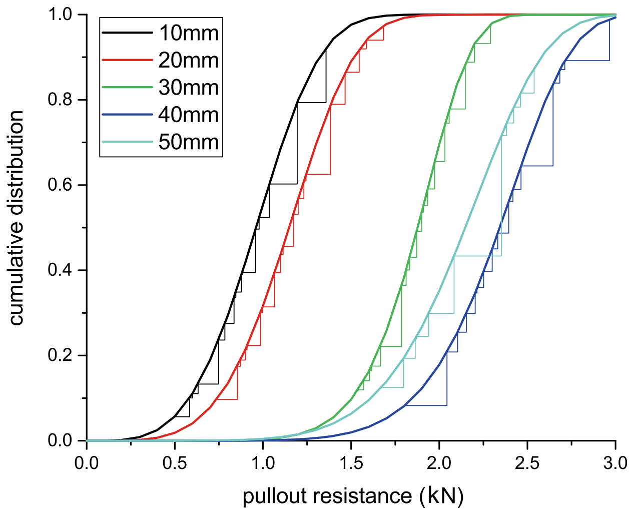

Fig. 4 The cumulative distribution of pullout resistance

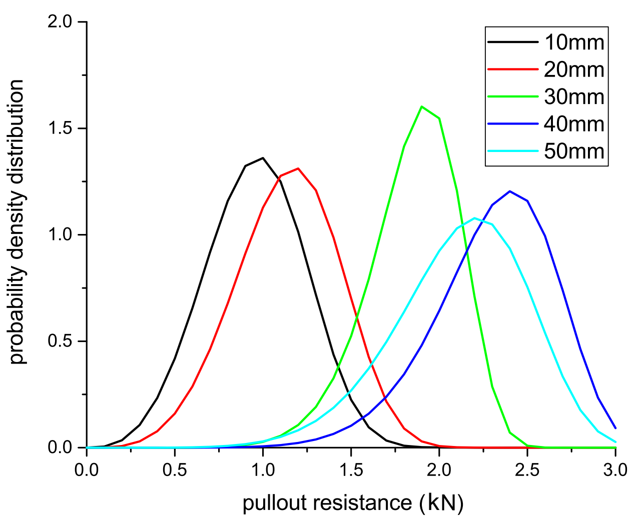

Fig. 5 The probability density distribution of pullout resistance

Group A-20:

$$F(x) = 1 - \exp\left[-\left(\frac{x}{1.2496}\right)^{4.3397}\right] \tag{11}$$

$$f(x) = 3.47287 \times \left(\frac{x}{1.2496}\right)^{3.3397} \times \exp\left[-\left(\frac{x}{1.2496}\right)^{4.3397}\right] \tag{12}$$

Group A-30:

$$F(x) = 1 - \exp\left[-\left(\frac{x}{1.9597}\right)^{8.5448}\right] \tag{13}$$

$$f(x) = 4.36026 \times \left(\frac{x}{1.9597}\right)^{7.5448} \times \exp\left[-\left(\frac{x}{1.9597}\right)^{8.5448}\right] \tag{14}$$

Group A-40:

$$F(x) = 1 - \exp\left[-\left(\frac{x}{2.4532}\right)^{7.9701}\right] \tag{15}$$

$$f(x) = 3.24886 \times \left(\frac{x}{2.4532}\right)^{6.9701} \times \exp\left[-\left(\frac{x}{2.4532}\right)^{7.9701}\right] \tag{16}$$

Group A-50:

$$F(x) = 1 - \exp\left[-\left(\frac{x}{2.2709}\right)^{6.5786}\right] \tag{17}$$

$$f(x) = 2.89691 \times \left(\frac{x}{2.2709}\right)^{5.5786} \times \exp\left[-\left(\frac{x}{2.2709}\right)^{6.5786}\right] \tag{18}$$

From Fig. 4, all the pullout resistance of different welded depth was complied with the Weibull distribution. So the Weibull distribution may be used in the analyses of wood dowel welding reasonably. From Table 2 and Fig. 5, the pullout resistance of depth 30 mm showed the lowest standard deviation. From Figs. 4 and 5, the 95% reliability pullout resistance could be calculated in Table 5.

Linear regression analyses between pullout resistance and welded depth

To analyze the statistical significance of the factor welded depth, the analysis of variance was carried out [18]. When the level of significant was $\alpha = 0.05$, the analysis result of variance was $F = 88.596 > 18.5$. According to the results of pullout resistance, factor welded depth showed high significant difference. Meanwhile, the significant result of homogeneity test for variance was $0.409 > 0.05$. The test result met the requirement of homogeneity of variance. So the mean values were used to be analyzed below.

From Fig. 2, pullout resistance of 50 mm was lower than that of 40 mm. To study the linear relation between pullout resistance and welded depth, the pullout resistance of 50 mm was not considered. Figure 6 showed the linear relation in the range of 10–40 mm.

$$Y = 51.06X + 265.5. \tag{19}$$

In Fig. 6, the red line was the linear relation (Eq. 19) obtained from Origin 10.1 software. Based on the F-method of inspection, a test of significance of the linear regression was performed, where U and Q were the regression and residual sum of squares, respectively. When the level of significance was $\alpha = 0.05$, the $F_{0.95}(1, 2) = 18.5$. According to Eq. 19, $U = 1{,}303{,}562$ and $Q = 31236.2$ were calculated, and then $F = 2 \times \frac{1303526}{31236.2} = 83.46 > 18.5$. The result indicated that a significant linear regression exists between the pullout resistance and welded depth. From

Table 5 The 95% reliability pullout resistance of different welded depth

Welded depth(mm)	10 mm	20 mm	30 mm	40 mm	50 mm
95% reliability pullout resistance (N)	482	631	1385	1690	1446

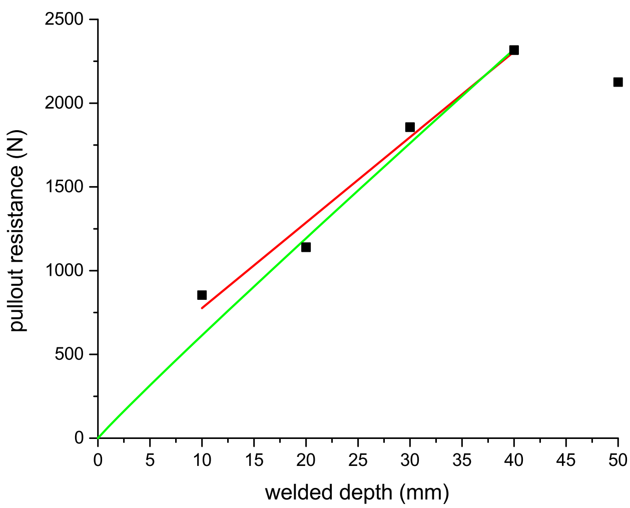

Fig. 6 The linear relation and Eckelman equation between pullout resistance and welded depth (10–40 mm)

Table 6, the biggest error 12.87% between calculated value and test value was at 20 mm. The errors existed in the other three depths were less than 9.12%. So the linear relation could not fit the data accurately.

Eckelman [19] studied Eq. 20 of pullout resistance for wood dowel with adhesive.

$$F = 1.19 \times D \times L^{\alpha} \times (\tau_{dowel} + \tau_{substrate}) \times a \times b \times c \tag{20}$$

where D was the diameter of wood dowel, 10 mm was used in this study; L was the depth; τ_{dowel} was the shear strength of wood dowel; $\tau_{\text{substrate}}$ was the shear strength of substrate; a was the parameter of bonding; b was the parameter of interference fit; c was the parameter of wood dowel surface shape, 0.9 was selected for the spiral wood dowel in this study.

According to Tables 1 and 3 and Fig. 3f, g, the pullout resistance of group B was considered to be the maximum value, because the fracture occurred in the wood dowel rather than welding interface. So the $a \times b$ in the formula was calculated by $a \times b = 1857/4697 = 0.4$. τ_{dowel} and $\tau_{\text{substrate}}$ were 7.8 and 7.9 MPa, respectively. In the previous study of Eckelman, α was 0.89. While in this study, 0.97 was calculated by the 30 mm depth. Based on these parameters, the green line could be drawn in Fig. 6. And the errors between calculated values and test values are shown in Table 6. The errors were less than 7.89% except the depth 10 mm.

So in this study, the linear relation and Eckelman formula did not fit the data accurately.

Nonlinear regression analyses between pullout resistance and welded depth

Based on the distribution of data, the pullout resistance of depth 50 mm was lower than that of depth 40 mm. And Kanazawa obtained the pullout resistance of 1000 N for depth 15 mm [5]. In this study, the pullout resistance of depth 10 mm was 854 N. Hence, little difference existed in depth 10 and 15 mm. All of these characteristics were similar to the form of sine curve. So the nonlinear relation sine function was found between pullout resistance and welded depth. Equation 21 of this nonlinear relation is showed in Fig. 7.

$$Y = 1593.88 + 742.12 \times \sin\left[\pi \times \frac{X - 26.51}{31.47}\right] \tag{21}$$

If $T = \sin[\pi \times (X - 26.51)/31.47]$, Eq. 21 could be rewritten to Eq. 22.

$$Y = 1593.88 + 742.12\text{T} \tag{22}$$

And then a test of significance of the linear regression was performed. When the level of significance was $\alpha = 0.05$, the $F_{0.95}(1, 3) = 10.1$. According to Eq. 22, $U = 1{,}598{,}342$ and $Q = 94$ were calculated, and then $F = 3 \times \frac{1598342}{94} = 51010.91 > 10.1$. The result indicated that a significant linear regression exists between the pullout resistance and T. So a significant nonlinear regression existed between the pullout resistance and welded depth [18].

According to this Eq. 21, the differences between calculated values and test values are shown in Table 7. All the data of five depths were fit accurately with the errors less than 0.44%. In the future study, the depth of 25 and 60 mm should be tested to verify Eq. 21. Based on Eq. 21, the theory of maximum pullout resistance of 2336 N at depth 42.23 mm was calculated. Meanwhile, the fastest growing

Table 6 The errors of linear relation and Eckelman equation for different welded depth

Fit methods	10 mm (%)	20 mm (%)	30 mm (%)	40 mm (%)
Linear relation	9.12	12.87	3.21	0.39
Eckelman formula	26.46	7.89	1.88	3.97

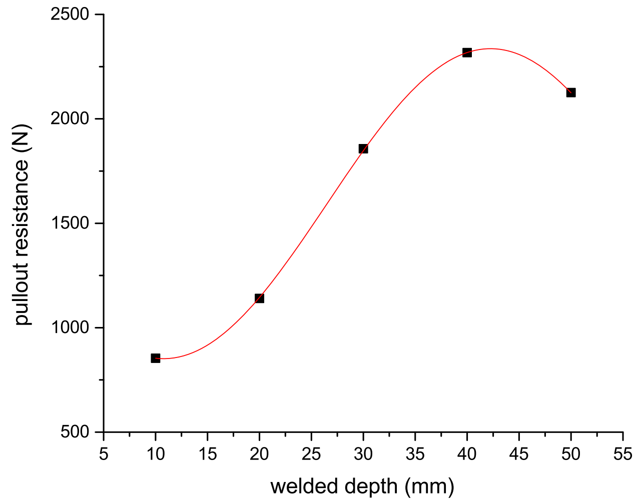

Fig. 7 The sine relation between pullout resistance and welded depth

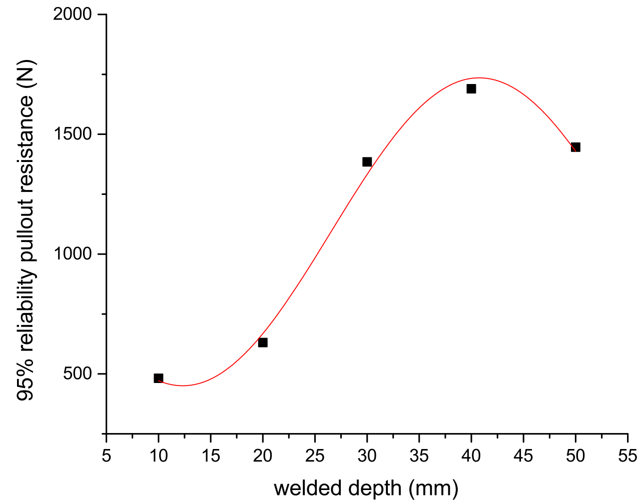

Fig. 8 The sine relation between 95% reliability pullout resistance and welded depth

Table 7 The errors between test value and calculated value for nonlinear relation

Group	Test value (N)	Calculated value (N)	Error (%)
A-10	854	854	0
A-20	1140	1145	0.44
A-30	1857	1849	0.43
A-40	2317	2318	0.04
A-50	2126	2124	0.09

Group A-10 meant the untreated group, and the number 10 meant the welded depth 10 mm

Table 8 The errors between 95% reliability pullout resistance and calculated value by Sine function

Group	95% reliability pullout resistance (N)	Calculated value (N)	Error (%)
A-10	482	472	2.07
A-20	631	669	6.02
A-30	1385	1334	3.68
A-40	1690	1733	2.54
A-50	1446	1429	1.18

Group A-10 meant the untreated group, and the number 10 meant the welded depth 10 mm

stage was at depth 20–30 mm from Fig. 7. So in the future study, the welded depth need to be selected between 30 and 40 mm.

From Table 5, 95% reliability pullout resistance was calculated which was much lower than the mean value of pullout resistance. It was similar to the sine function existed in the mean value of pullout resistance, the nonlinear relation (Eq. 23) of 95% reliability pullout resistance is studied in Fig. 8.

$$Y = 1092.98 + 642.45 \times \sin\left[\pi \times \frac{X - 26.54}{28.44}\right] \tag{23}$$

If $T = \sin\,[\pi \times (X - 26.54)/28.44]$, Eq. 23 could be rewritten to Eq. 24.

$$Y = 1092.98 + 642.45T \tag{24}$$

According to Eq. 24, $U = 1{,}141{,}365$ and $Q = 6283$ were calculated, and then $F = 544.98 > 10.1$. The result indicated that a significant linear regression exists between the 95% reliability pullout resistance and T. So a significant nonlinear regression existed between the pullout resistance and welded depth.

The errors are shown in Table 8. All the errors were less than 6.02%. So in this study, pullout resistance and 95% reliability pullout resistance were fit accurately by the sine function. While from Fig. 8, the highest error may occur at the depth 15 mm.

Based on Eq. 23, the theory of maximum 95% reliability pullout resistance of 1735 N at depth 40.75 mm was calculated. And the fastest growing stage was at depth 20–30 mm. These results also explained that the welded depth should not exceed 40 mm. For consideration of reducing processing difficulty and rapture rate of wood dowels, depth 30 mm was selected for the next study.

The influence of immersing in $CuCl_2$ for 30 min on welding temperature

From Table 3, pullout resistance of group B showed the highest value. The fracture of the specimens from group B occurred in the wood dowel surface instead of welding interface. So it could be inferred that the pullout resistance of wood dowel welding in this study has been reached the maximum value. According to this result, the difference of temperature between them during welding process should

Table 9 The highest temperature of group A-30 and group B

The highest temperature (°C)				Pullout resistance (N)
	Point 1	Point 2	Point 3	
Group A-30				
1	261.5	199.5	103.5	1302
2	260.7	164.6	130.2	2186
3	264.4	223.9	106.6	2328
4	262.3	135.7	100.3	1086
5	253.3	197.1	99.1	2822
Mean value	260.4	184.2	107.9	1944.8
Standard deviation	4.22	34.33	12.78	728.91
Variable coefficient (%)	1.62	18.64	11.84	37.48
Group B				
1	223.8	203.8	145.7	3396
2	229.8	209.3	95.8	2712
3	212.7	197.7	75.0	2590
4	236.2	221.2	79.6	2654
5	219	185.9	121.9	2746
Mean value	224.3	203.6	103.6	2819.6
Standard deviation	9.15	13.14	29.84	327.63
Variable coefficient (%)	4.08	6.45	28.80	11.62

Group A-30 meant the untreated group, and the number 30 meant the welded depth 30 mm

Group B meant the treated group with wood dowels immersed in $CuCl_2$ for 30 min

be tested to explain the reason of improved pullout resistance.

The highest temperature of three test points for group A-30 and group B is shown in Table 9. In both groups, the temperature of point 1 was the highest, and the point 3 was the lowest. Based on the analyses of pullout resistance, almost no welding occurred near the point 3 areas (Fig. 3g).

Test points 2 and 3 of group A-30 showed the highest standard deviation. The pullout resistance was affected significantly by the temperature of points 2 and 3. The specimen 4 showed the lowest pullout resistance among group A-30, because low temperature could not provide sufficient heat to produce molten materials around the wood dowel. Similar conclusion could be obtained in group B. The specimen 3 showed the lowest pullout resistance, while the specimen 1 showed the highest pullout resistance among group B.

The biggest difference between group A-30 and group B was the temperature of point 1. The mean temperature of point 1 for group A-30 was 260.4 °C, while that for group B was 224.3 °C. Wood dowels of group B was immersing in $CuCl_2$ solution for 30 min. During this immersing process, the wood dowels was acid corrosion to form a soften materials in the surface. Compared with the group A-30, the soften materials in the surface decreased the friction between the wood dowel and the substrate hole. Meanwhile, the temperature of point 2 for group B was higher than group A-30, which could promote the welding around point 2. According to the phenomenon and results, 260 °C was an excessive temperature, while 224.3 °C was the better choice for welding in this study.

Conclusions

In group A, group A-40 exhibited higher pullout resistance than the other welded depths. In the same welded depth of 30 mm, group B specimens with dowels immersed in $CuCl_2$ solution for 30 min exhibited the highest pullout resistance than the other specimens. The failure of group B occurred on the surface of the wood dowels instead of welding interface. According to the failure behavior, the pullout resistance of group B was considered to be the maximum theory pullout resistance in the welded depth of 30 mm.

Weibull distribution could be applied reasonably to analyze pullout resistance of different welded depth. The linear simulation and Eckelman formula could not fit the relation of pullout resistance and welded depth. While the nonlinear simulation of sine function $Y = 1593.88 + 742.12 \times \sin\left[\pi \times \frac{X-26.51}{31.47}\right]$ could fit the relation accurately.

Based on the Weibull distribution, 95% reliability pullout resistance was calculated. The nonlinear simulation of sine function $Y = 1092.98 + 642.45 \times \sin\left[\pi \times \frac{X-26.54}{28.44}\right]$ also existed between 95% reliability pullout resistance and welded depth.

Both group A-30 and group B, the temperature of point 1 was the highest, and the point 3 was the lowest. The pullout resistance was affected significantly by the temperature of point 2 and 3. For point 1, 260 °C was an excessive temperature, while 224.3 °C was the better choice for welding in this study.

In the future study, finite element analyses and the water resistance of rotation welding will be studied. The practical application of rotation welding with acidizing or alkaline treatment will also be considered for the furniture and construction industry.

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Author contribution statement Ying Gao and Songlin Yi designed the experiment, Xudong Zhu and Chun Ni performed the experiment and analyzed data; Jirong Zhang and Xiangya Luo completed pullout resistance test; Xudong Zhu prepared and edited the manuscript, and Ying Gao reviewed and directed the manuscript.

Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest.

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