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WITHDRAWAL STRENGTH OF WELDED DOWEL JOINTS MADE OF BIRCH AND LARCH WOOD

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ABSTRACT

This study examined the mechanics and temperature during a wood dowel welding process. The test results indicated that the welded depth 40 mm showed the highest pullout resistance. Based on the mechanics and surface morphology, welded depth 30 mm was the optimal parameter. A nonlinear relation existed between pullout resistance and welded depth. The highest temperature of six test points was studied in group of welded depth 30 mm. With the increasing of depth, the highest temperature of six test points showed the decreased trend. A linear relation was found between the highest temperature of welding interface and the depth.

KEYWORDS: Welded joints, pullout resistance, welded depth, temperature distribution.

INTRODUCTION

Wood dowel welding creates a new bonding interface layer through the friction between the wood dowels and substrate holes. During this process, some wood components are softened, fused, and eventually become solidified until the friction stops. The properties of welded joints could be influenced by rotation speed, insertion speed, moisture content, and welded depth (Sandberg et al. 2013, Zhou et al. 2014).

The influence of rotation speed and moisture content were studied on welded joints. Leban found that the best pullout resistance could be obtained in the rotation speed range of 1200-1600 rpm (Leban et al. 2008). Furthermore, it was found that the welded joints with rotation speed of 1000 and 1500 rpm showed similar pullout resistance (Rodriguez et al. 2010). And the similar conclusion was found in the study of Chedeville et al. (2005). However, the significant variance could be found between pullout resistance and moisture content of wood dowel. Welded joints manufactured by wood dowels with 1% moisture content could improve the pullout resistance by 57.66% than that of wood dowels with 12% moisture content (Kanazawa et al. 2005). This could be caused by the dry wood dowels could inflate after absorbing water from the environment. Then wood dowels with 2% moisture content were used in other studies (Pizzi et al. 2006, Stamm et al. 2011).

With a slow inserting speed, the welding time increases and more friction occurs between wood dowels and substrate holes, which results in more molten materials being generated and increased frictional weight loss of the wood dowels. In the study by Belleville et al. (2013a), the optimum inserting speeds for maple and birch were 25 mm·s^{-1} and 16.7 mm·s^{-1}, respectively. No obvious difference was found between the inserting speeds of 16.7 mm·s^{-1} and 25 mm·s^{-1} for birch. However, specimens could not be prepared at a rotation speed of 1000 rpm and inserting speed of 25 mm·s^{-1}. The welding process generated a lot of smoke and carbonization at a rotation speed of 2500 rpm and inserting speed of 12.5 mm·s^{-1} welding, inserting speed is referred to as the welding time (Belleville et al. 2013a, Pizzi et al. 2013).

On the other hand, welded depth was an important factor to the welded joints. The pullout resistance of welded depth 22 mm could get 2145 N, and 2500 N could obtained when the welded depth was 46 mm (Leban et al. 2008). However, the pullout resistance of welded depth 30 mm was twice bigger than that of welded depth 15 mm (Kanazawa et al. 2005). And in the other studies, welded depth 20-30 mm was frequently used (Pena et al. 2015, Belleville et al. 2013b, Omrani et al. 2008). Several researches just focused on the optimal pullout resistance with the certain welded depth, so the significant of welded depth and the relation between pullout resistance and welded depth should be studied.

The friction generated between the wood dowels and substrate holes can cause the temperature to rapidly increase. Using the theoretical formula from Zoulalian and Pizzi (2007), it was found that the highest temperature at the welding interface could reach 183°C using the optimum parameters for beech. However, Rodriguez et al. (2010) found that the highest temperatures for birch and maple were over 300°C. Another study showed that the temperature could be influenced by the rotation speed. For both birch and maple, the temperature could reach 244.1°C and 282.6°C at 1000 rpm, 281.1°C and 297.4°C at 1500 rpm, and 328.6°C and 327.3°C at 2500 rpm, respectively. Meanwhile, both birch and maple specimens showed the best pullout resistance at temperatures of 244.1°C and 282.6°C, respectively, and a rotation speed of 1000 rpm (Belleville et al. 2013a). According to this analysis, with an increased rotation speed, the temperature at the welding interface could reach 300°C and the pullout resistance could be affected by the temperature. Most researches were studied the highest temperature in the welding interface, but the temperature at different depth along the welding interface was not tested and analyzed. With the temperature distribution in the welding interface, several chemical changes could be studied in the future.

Based on the researches above, birch wood dowel and Chinese larch substrate was used as welding materials to study the mechanics and welding interface temperature in this study. The influence of the pullout resistance on the welded specimen was analyzed by setting different welded depth. The regression analyses between welded depth and pullout resistance was studied, as well as the highest temperature and depth.

MATERIAL AND METHODS

Materials

Wood dowels, 10 mm in diameter and 100 mm in length, were fabricated from birch wood (*Betula pendula*; Crownhomes, Jiangsu, China). The air dried density at 12% MC of the birch dowel was 557 kg·m^{-3}. Chinese larch (*Larix gmelinii*; Crownhomes, Jiangsu, China) slats with the dimensions of 40 mm (Tangential) × 50 mm (Radial) × 500 mm (Longitudinal) were used as substrates. The air dried density at 12% MC of the larch was 680 kg·m^{-3}.

All of the wood dowels were placed in an oven at 63°C until a 2% MC was reached. The tensile strength of the wood dowels was 4864 N. The decision to use the temperature of 63°C was based on preliminary experiments. It was found that the wood dowels could achieve the desired MC over 2 days at that temperature with minimal warping or cracking. All of the substrates were exposed to a temperature of 20°C and RH of 60% until reaching a 12% equilibrium MC.

Specimen preparation

The tangential section of wood substrates were pre-drilled with holes 8 mm in diameter and 30 mm in depth using a drilling machine (Proxxon TBH Type 28 124, Proxxon, Stuttgart, Germany). Next, the wood dowels were welded into the pre-drilled holes in the substrates to create bonded joints at a high-speed rotation of 1080 rpm (Chedeville et al. 2005, Leban et al. 2008, Rodriguez et al. 2010). The inserted part of the dowel became conical from cylinder in shape. Black molten material spilled out of the welding interfaces because of the abrasion during the welding process. Rotation of the wood dowel stopped when fusion and bonding was achieved after 3 sec (Belleville et al. 2013a, Pena et al. 2016). Twenty specimens were prepared for each group, but several specimens were broken during welding or the testing process. According to the different depth, test group was divided into group D-10 ~ group D-50 (Tab 1).

Methods

Pullout resistance test

After welding, the wood slats were cut into 10 parts that were even in length, so that every welded dowel was 40 (T) ×50 (R) ×50 mm (L) in size. The specimens were conditioned at 20°C and 60 % RH for 7 days before the tests were conducted.

The pullout resistance of the specimens was tested using a universal testing machine (Fig. 1, WDW-300E; Jinan Popwil, Jinan, China) that pulled the welded wood dowels out of the substrate at a speed of 2 mm·min^{-1} (O'Loinsigh et al. 2012). The specimens were fixed by clamping the dowel into the jaw of a fixed beam, while the substrate block was fixed to a mobile beam via a metal framework.

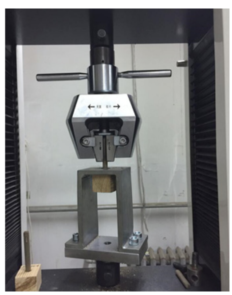

Fig. 1: WDW-300E universal testing equipment.

Reliability analyses

The reliability analysis of data has been widely used in the construction filed. In this study, the Weibull distribution was applied to study the reliability of pullout resistance. The Weibull distribution function *(F(x))* was determined according to Eq. 1, and the probability density function *f(x)* was calculated according to Eq. 2, which was transformed by a differential of Eq. 1,

$$F(x) = 1 - e^{-\left(\frac{x - a_0}{\hat{a}}\right)} \quad (1)$$

$$f(x) = \frac{\acute{a}}{\hat{a}} \times \left(\frac{x - a_0}{\hat{a}}\right)^{\acute{a}-1} \times e^{-\left(\frac{x - a_0}{\hat{a}}\right)^{\acute{a}}} \quad (2)$$

where: α, β, and a_0 - the shape, scale, and location parameters, respectively.

The basic shape of curve was determined by α. The β can zoom in or out of the curve. And the variable x is the pullout resistance.

Temperature test

The temperature was tested using six thermocouple sensors with data collecting device (Beijing heshixingye Technology CO., Ltd., XSL-A16XS1V0, China). Six sensors were set in six different depths along 5 mm, 10 mm, 15 mm, 20 mm, 23 mm, and 28 mm (Fig. 2).

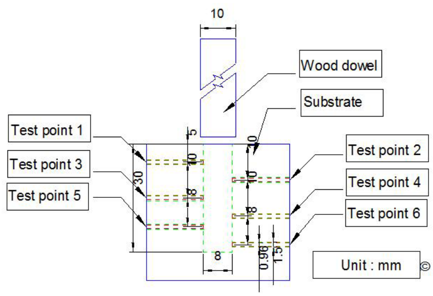

Fig. 2: Technical drawing of test points for monitoring temperature.

The depth 28 mm of the sensor at test point 6 was selected due to the pullout resistance and surface morphology of welded depth 30 mm (Fig. 3-3). The response speed of the K-type thermocouple sensor was 0.34 ms. Origin 10 software was used to analyze the statistics.

RESULT AND DISCUSSION

Pullout resistance and surface morphology

20 replicate welding specimens were tested for each group with different welded depth. The pullout resistance results of different welded depth were summarized in Tab. 1.

Tab. 1: Pullout resistance of welding specimens for different welded depths.

Welded depth (mm)	Mean value (N)	Maximum value (N)	Minimum value (N)	COV* (%)
10	854	1358	498	27.28
20	1140	1684	738	24.56
30	1857	2290	1536	12.28
40	2317	2966	1800	13.12
50	2126	2538	1672	14.63

*COV - coefficient of variation.

With the increasing of welded depth, the welding area of welding interface increased, and the pullout resistance showed the increasing trend. From Tab. 1, group D-40 with welded depth 40 mm showed the best pullout resistance, which was 24.77 % and 8.98 % higher than group D-30 and group D-50, respectively. The surface morphology of each group was showed in Fig. 3. From Fig. 3-1, all the welding interface of group D-10 with welded depth 10 mm was covered with black molten materials. And some substrate wood could be found in the welding interface on the wood dowel after pullout test. On the other hand, for group D-20 with welded depth 20 mm, few black molten materials existed at the tip of the wood dowel (Fig. 3-2). The same phenomenon could be found in group D-30 with welded depth 30 mm. 2 mm at the tip of the wood dowel was lack of black molten materials (Fig. 3-3) which was used to set the temperature monitoring sensor depth. And then for group D-40 and group D-50, they were difficult to operate, because the welding friction of group D-40 and group D-50 existed between wood dowel and substrate hole was much bigger than that of group D-10 ~ group D-30. The wood dowels were easy to fracture during the welding process, because of the excessive torque. Furthermore, the phenomena of a lot lack of black molten materials were found in their welding interface, especially for group D-50 with welded depth 50 mm (Fig. 3-4 and Fig. 3-5). The phenomena of lack of black molten materials could be caused by the excessive friction and out of shape of wood dowel during the welding process. With the increasing welded depth, the welding time increased, more black molten materials could be generated from the welding interface. But the inserted part of the wood dowel became conical in shape. When the welded depth was 10 mm ~ 30mm, the conical shape of wood dowel was formed. While for welded depth 40 mm ~ 50 mm, the diameter of the end of the wood dowel was similar to group D-30, which indicated no new friction occurred between the end of the wood dowel and substrate hole for group D-40 and group D-50 during the welding process. So for group D-40 and group D-50, black molten materials could not be found at the end of wood dowel.

Fig. 3-1: Test group D-10.

Fig. 3-2: Test group D-20.

Fig. 3-3: Test group D-30.

Fig. 3-4: Test group D-40.

Fig. 3-5: Test group D-50.

Welded depth one-way analysis of variance

From Tab. 1, the pullout resistance was affected by the different welded depth. The pullout resistance of group D-30 was 62.89 % higher than that of group D-20. The increase in amplitude between these two groups was the biggest. And for group D-10 and group D-20, group D-30 and group D-40, group D-40 and group D-50, the increase in amplitude was 33.49 %, 24.77 % and 8.24 %, respectively. The homogeneity test for variance is shown in Tab. 3.

Tab. 2: Welded depth one-way analysis of variance.

Sources of variation	Quadratic sum	Degree of freedom	Mean square	F	Significance
Among groups	26015776.507	4	6503944.127	88.596	0.000
Within groups	5726058.674	78	73411.009		
Sum	31741835.181	82			

Tab. 3: Homogeneity test for variance.

Levene statistics	Degree of freedom 1	Degree of freedom 2	Significance
1.007	4	78	0.409

Tab. 4: Multiple comparison results with Tukey HSD method.

Depth	Depth	Mean difference	Standard deviation	Significance	95% Confidence interval	
					Lower-bound	Upper-bound
10	20	-285.36667*	92.54522	0.023	-543.8098	-26.9235
	30	-1002.70877*	93.58314	0.000	-1264.0504	-741.3671
	40	-1462.97778*	94.72305	0.000	-1727.5028	-1198.4528
	50	-1271.68485*	107.55369	0.000	-1572.0409	-971.3288
20	10	285.36667*	92.54522	0.023	26.9235	543.8098
	30	-717.34211*	86.80027	0.000	-959.7418	-474.9424
	40	-1177.61111*	88.02806	0.000	-1423.4396	-931.7826
	50	-986.31818*	101.70683	0.000	-1270.3462	-702.2902
30	10	1002.70877*	93.58314	0.000	741.3671	1264.0504
	20	717.34211*	86.80027	0.000	474.9424	959.7418
	40	-460.26901*	89.11861	0.000	-709.1429	-211.3951
	50	-268.97608	102.65216	0.076	-555.6440	17.6918
40	10	1462.97778*	94.72305	0.000	1198.4528	1727.5028
	20	1177.61111*	88.02806	0.000	931.7826	1423.4396
	30	460.26901*	89.11861	0.000	211.3951	709.1429
	50	191.29293	103.69242	0.356	-98.2800	480.8659
50	10	1271.68485*	107.55369	0.000	971.3288	1572.0409
	20	986.31818*	101.70683	0.000	702.2902	1270.3462
	30	268.97608	102.65216	0.076	-17.6918	555.6440
	40	-191.29293	103.69242	0.356	-480.8659	98.2800

Welded depth one-way analysis variance was carried out to analyze the statistical significance of the factor welded depth (Tab. 2). According to the analysis results, when the level of significant was 5 %, the result of variance analysis was $F = 88.596 > 2.53$. Factor welded depth showed the 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 in this study.

Based on the significant difference of the factor welded depth, the significant of different level of welded depth was studied by the multiple comparison method. According to the homogeneity of variance, the method of Tukey HSD was selected to analyze the difference among the levels of welded depth (Tab. 4). If the significance was greater than 0.05, the difference between the two welded depth showed non-significant. From Tab. 4, the significance between two welded depths was different, especially for welded depth 50 mm. The difference between welded depth 30 mm and 50 mm was not significant, and the same phenomenon could be found between welded depth 40 mm and 50 mm. Combined with the previous pullout resistance analysis, the welded depth 50 mm should be avoided in the next study, and the welded depth 30mm was the optimal parameter in this study.

Relation between pullout resistance and welded depth

According to the pullout resistance of different welded depth, nonlinear regression analyses were carried out in this study. Based on the distribution of data, the pullout resistance of welded depth 50 mm was lower than that of welded depth 40 mm. And the pullout resistance of specimens with welded depth from 10 mm to 40 mm showed the increased trend. All of these characteristics were similar to the form of Gauss distribution curve. So the nonlinear relation Gauss function was analyzed between pullout resistance and welded depth by Origin 10.1 software. The nonlinear regression analyses Eq. 3 could be generated.

$$Y = 738.54 + 1619.93 \times e^{-\frac{(x-42.24)^2}{375.83}} \tag{3}$$

where: Y - pullout resistance, X - welded depth.

If $T = e^{-\frac{(x-42.24)^2}{375.83}}$, then the Eq. 5 could be rewritten to Eq. 4.

$$Y = 738.54 + 1619.93\ T \tag{4}$$

Based on the F-method of inspection, a test of significance of the linear regression was performed. *U* and *Q* were the regression and residual sum of squares, respectively.

$$U = \hat{b}^2 \sum_{i=1}^{n} \left(t_i - \bar{t}\right)^2 = 1604961 \tag{5}$$

$$Q = \sum_{i=1}^{n} \left(y_i - \hat{y}_i\right)^2 = 2691.473 \tag{6}$$

The coefficient of association could be calculated as below.

$$r^2 = \frac{U}{U + Q} = 0.998326 \tag{7}$$

And then r = 0.999163.

When the level of significance was α = 0.05, *F*-method of inspection was calculated.

$$F = (n-2)\frac{U}{Q} = 1788.94 > F_{0.95}(1,3) = 10.1 \tag{8}$$

The result of the coefficient of association r and F-method of inspection indicated that a significant linear relation existed between pullout resistance Y and conversion variable T. So a significant nonlinear relation existed between the pullout resistance and welded depth (Fig. 4).

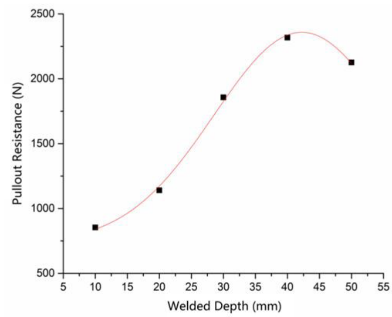

Fig. 4: The Gauss relation between pullout resistance and welded depth.

Tab. 5: Difference between the calculated value and test value of the pullout resistance.

Welded depth (mm)	Test value (N)	Calculated value (N)	Error (%)
10	854	840.49	1.61
20	1140	1172.99	2.81
30	1857	1825.90	1.70
40	2317	2336.99	0.86
50	2126	2118.65	0.35

According to Eq. 3, the differences between calculated values and test values were showed in Tab. 5. All the data of the five welded depths were fit accurately with the errors less than 2.81%. Kanazawa obtained the pullout resistance of 956 N for welded depth 15 mm. Five specimens with welded depth 15 mm were tested in this study as a verification test. The mean value of the pullout resistance was 971 N. And the calculated value of Eq. 3 was 963 N for welded depth 15 mm. A little difference existed in these three values. On the other hand, the maximum pullout resistance was calculated by Eq. 3. It was 2358 N with the welded depth 42.24 mm. And then the verification test of five specimens with welded depth 42 mm was carried out. The mean value of the pullout resistance was 2342 N. Meanwhile, the fastest growing stage was at depth 20 mm ~30 mm from Fig. 4, so in the future study, the welded depth need to be selected between 30 mm and 40 mm.

The reliability analyses of pullout resistance

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, pullout resistance with 0 N was reasonable. The Weibull distribution function Eq. 1 could be rewritten (Fu et al. 2001, Hengwu et al. 2003).

$$F(x) = 1 - e^{-\left(\frac{x}{\beta}\right)^{\alpha}} \tag{9}$$

Both of the sides were taken the logarithm, Eq. 9 could be turned to

$$ln\,[-ln\,(1-F(x))] = \alpha lnx - \alpha ln\beta \tag{10}$$

In the Weibull distribution probability graph, $ln(x)$ and $ln\,[-ln\,(1-F(x))]$ were set to X-coordinate and Y-coordinate, respectively. So the Eq. 10 was rewritten to Eq. 11. In this formula, $b = \alpha$ and $a = -\alpha.ln(\beta)$ were considered (Chunjie et al. 2005, Mingchao et al. 2008).

$$Y = b \cdot X + a \quad (11)$$

For the five welded depth, five equations could be set, respectively.

$$Y = 3.7782\ X - 0.2143 \quad (12)$$
$$Y = 4.3397\ X - 0.9668 \quad (13)$$
$$Y = 8.5448\ X - 5.7489 \quad (14)$$
$$Y = 7.9701\ X - 7.1523 \quad (15)$$
$$Y = 6.5786\ X - 5.3957 \quad (16)$$

Tab. 6: Parameter α and β of the five different welded depths groups.

Welded depth (mm)	10	20	30	40	50
α	3.7782	4.3397	8.5448	7.9701	6.5786
β	1.0584	1.2496	1.9597	2.4532	2.2709

Based on the Eq. 12 ~ 16, the parameters α and β were calculated in the Tab. 6. The parameter α of welded depth 30 mm was the biggest. And parameter α of welded depth 10 mm was the lowest. Parameters α of welded depth 10 mm, 20 mm, 40 mm and 50 mm were 55.78%, 49.21%, 6.73% and 23.01% smaller than that of welded depth 30 mm, respectively. For welded depth 10 mm and 20 mm. black molten materials were generated from the friction between wood dowel and substrate hole. But with the time limit, the amounts of black molten materials were smaller than that of welded depth 30 mm ~ 50 mm. On the other hand, the welding time of welded depth 10 mm and 20 mm was shorter than that of the other three test groups. The black molten materials might not flow uniformly. Therefore, the pullout resistance of welded depth 10 mm and 20 mm showed greater dispersion. For welded depth 40 mm and 50 mm, the data discretization of pullout resistance could be caused by the lack of black molten materials at the end of the wood dowel. Based on the parameter α, the pullout resistance of group D-30 showed the best reliability. The same conclusion could be inferred from the coefficient of variation in Tab. 1. According to these analyses, welded depth 30 mm was an optimal parameter in this study.

Net welded force between wood dowel and substrate hole

The welded specimen was composed of wood dowel and substrate. The diameter of wood dowel was 10 mm, and the diameter of the predrilled hole in the substrate was 8 mm. So interference fit was existed between them, and a large amount of friction might generate after welding process. In order to discuss the net welded force for different welded depth, friction between wood dowel and substrate hole was tested. Wood dowel was hammered into the predrilled substrate hole directly. And then the pullout resistance of hammered specimens was tested (Tab. 7). And the net welded force was calculated by pullout resistance of welded specimen minus friction (Tab. 8).

From Tab. 7, with the increasing hammered depth, the friction showed the increased trend. Ten hammered specimens were prepared for each depth. But during the hammered process, 1, 1, 0, 2 and 4 specimens were cracked or broken for hammered depth 10 mm, 20 mm, 30 mm, 40 mm and 50 mm, respectively. The friction of hammered depth 10 mm was the lowest, because inadequate extrusion existed between wood dowel and substrate hole. For hammered depth 20 mm ~ 50 mm, with the increased depth, the coefficient of variation showed the decreased trend. This could be caused by the increased stability of friction between wood dowel and substrate hole with less affected by the other factors.

Tab. 7: Friction of different depths for hammered specimens.

Hammered depth (mm)	Mean value (N)	Maximum (N)	Minimum (N)	COV (%)
10	101	196	50	59.22
20	686	1354	250	67.38
30	912	1526	506	34.76
40	1225	1700	654	25.30
50	1502	1756	1294	11.17

Tab. 8: Net welded force of different welded depths.

Welded depth (mm)	10	20	30	40	50
Pullout resistance (N)	854	1140	1857	2317	2126
Friction (N)	101	686	912	1225	1502
Net welded force (N)	753	454	945	1092	624

From Tab. 1 and Tab. 7, the net welded force could be calculated in Tab. 8. Because of the inadequate friction of hammered depth 10 mm, the net welded force of welded specimen could get 753 N. For welded depth 20 mm ~ 40 mm, with the increased depth, the net welded force showed the increased trend. On the other hand, for welded depth 50 mm, the net welded force was lower than that of welded depth 30 mm and 40 mm, because the pullout resistance was lower than that of welded depth 40 mm, but the friction was higher. Meanwhile, little difference of the net welded force existed between welded depth 30 mm and 40 mm. But it was difficult to manufacture the welding specimens of welded depth 40 mm and 50 mm. And from Fig. 3-3, the homogeneity of welded depth 30 mm was better than that of welded depth 40 mm. According to these analyses, it could be inferred that welded depth 30 mm was an optimal parameter in this study.

The influence of welded depth on welding temperature

From Fig. 3, the pullout resistance and surface morphology were different for five welded depths. The black molten materials also showed the different distribution. These phenomena could be caused by the friction temperature between wood dowel and substrate hole in different welded depth. According to this result, the difference of temperature between wood dowel and substrate hole during welding process should be tested to explain the reason of different distribution with black molten materials.

Tab. 9: The highest temperature of different welded depth for group D-30.

Samples	Test point 1	Test point 2	Test point 3	Test point 4	Test point 5	Test point 6
1	280.9	261.5	221.9	199.5	155.6	103.5
2	298.1	260.7	229.2	164.6	173.4	130.2
3	312.9	264.4	217.7	223.9	163.7	106.6
4	296.3	262.3	235.8	135.7	164.2	100.3
5	298.2	253.3	216.4	197.1	159.9	99.1
Mean value	297.28	260.44	224.20	184.20	163.36	107.94
Standard deviation	11.34	4.22	8.18	34.33	6.59	12.78

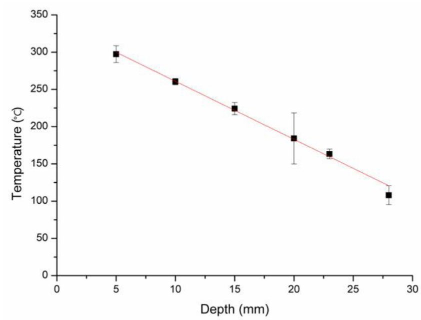

Fig. 5: Linear regression analyses of the highest temperature with each test point.

The highest temperature of six test points for group D-30 was shown in Tab 9. For all the test samples, the temperature of test point 1was the highest, and the test point 6 was the lowest. According to the pullout resistance and surface morphology, almost no black molten materials were generated around test point 6. This phenomenon could be caused by the lowest temperature generated from the welding process. Therefore, little friction rotation welding occurred after the welded depth 28 mm. This could be testified by the surface morphology of welded depth 40 mm and 50 mm. Based on the analyses, welded depth 30 mm could be the optimal parameter in this study.

Due to welding process time was short, the pyrolysis of wood components occurred in the short term. So the highest temperature of the welding interface in the different depth had significant influence on the molten material. Fig. 5 showed the linear regression relationship between the highest temperature and depth. The corresponding linear fitting formula was shown in Eq.17:

$$Y = -7.79 \cdot X - 338.76 \quad (17)$$

The correlation coefficient of the linear fitting formula was 99.36%, which indicated that the fitting precision of the linear fitting surface was high.

CONCLUSIONS

1. Welded depth 40 mm exhibited higher pullout resistance than the other welded depths. Welded depth 30 mm was the optimal parameter with high pullout resistance and evenly distributed black molten materials.
2. The Eckelman formula could not fit the relation of pullout resistance and welded depth. While the nonlinear simulation of Gauss function $Y = 738.54 + 1619.93 \times e^{-\frac{(x-42.24)^2}{375.83}}$ could fit the relation accurately.
3. The temperature of test point 1 was the highest, and the test point 6 was the lowest. The linear relationship $Y = -7.79X - 338.76$ was existed between the highest temperature and each depth.

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