Influence of the Depth of Friction-welded Dowels on the Strength of Rotary Welded Joints

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One of the important factors in rotary welding is the depth of welding of the dowel as well as the direction of welding of the dowel. In the studied interval (welding depth of 15 to 30 mm), the pull-out force increased when welding the dowel parallel to the wood grain and perpendicular to the wood grain. The strength of the welded joint increased from 15 to 20 mm, and then it continuously decreased towards a welding depth of 30 mm. The reason for this is that the tip of the dowel is intensively worn, and with a welding depth of 20 mm, it is approximately equal to the diameter of the hole. Therefore, by increasing the welding depth, the pull-out force increases slightly (due to the friction between the dowel and the hole wall), and the strength of the joint decreases. The highest joint strength was achieved at a welding depth of 20 mm for specimens welded parallel to the grain (PV) and specimens welded perpendicular to the grain (RTV). In welded joints where the dowels are loaded only by tensile force, it is recommended to use a welding depth of 30 mm.

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INTRODUCTION

Essential points of wooden construction are joints of the wooden elements. This is because they carry loads between elements and they retain the integrity of the wooden structure over its service life. Dowel joints are commonly used because of their simple construction and production, and this type of joint ensure satisfactory strength and elasticity (Paulenkova 1984; Zhang and Eckelman 1993; Dalvand *et al.* 2014; Vassiliou *et al.* 2016). Welding the wood achieves joints whose strength is comparable with the strength of glued joints. When welding wooden dowels to wooden bases by friction, it is possible to join the elements of wood, because the heat changes the structure of the wood. Heat generated due to friction softens and melts the chemical structure of wood (hemicelluloses, lignin and accessory substances). Cellulose fibers are intertwined in the melt thus formed. The smoke that appears as a result of welding consists of water vapor, CO_2, and degradation compounds from wood polymeric carbohydrates and from amorphous lignin (Pizzi *et al.* 2004; Kanazawa *et al.* 2005; Leban *et al.* 2008; Župčić 2010; Belleville *et al.* 2013; Župčić *et al.* 2023). The proportion of CO_2 emitted is very low, and neither CO nor methane is emitted due to the relatively low temperature of dowel welding (Omrani *et al.* 2008). During the welding process, the properties of welded joints could be influenced by insertion speed, density, welded depth, welding time, rotational frequency, wood species, direction of welding (parallel or perpendicular to the wood grain direction), width of growth rings, moisture content, welding temperature, interference fit, and pretreatments (Pizzi *et al.* 2004; Ganne-Chedeville *et al.* 2005; Bocquet *et al.* 2007; Leban *et al.* 2008; Rodriguez *et al.* 2010; Župčić *et al.* 2011; Auchet *et al.* 2012; Belleville *et al.* 2016; Župčić *et al.* 2022; Župčić *et al.* 2023). Welding effectiveness is directly associated with the properties of the original wood constituents, primarily lignin and carbohydrates (Belleville *et al.* 2013). Although lignin appears to be a major contributor in wood welding, the welded site also showed increased amounts of polysaccharide-derived products. Rotation welding of two wood sections at 1200 min^{-1} for 7 s at 2.5 MPa pressure could achieve good strength joints with mean tensile strength of 2190 N (Shukla *et al.* 2022). A higher frequency of rotation of the dowel increases the mobility of the melt moving away from the welding line, and the strength of the welded joint is reduced (Leban *et al.* 2008). By reducing the water content from 12% to 0%, the strength of the welded joint increases at rotation frequencies of 1165 min^{-1} and 1515 min^{-1} (Ganne-Chedeville *et al.* 2005).

The effect of welding depth on pull-out force was investigated by Zhu *et al.* (2017). The highest pull-out force was achieved by specimens where the dowels were welded to a depth of 40 mm. In the welded depth of 30 mm, specimens with dowels immersed in $CuCl_2$ solution for 30 min exhibited the highest pull-out force in comparison to the other specimens. According to Leban *et al.* (2008), the optimal welding depth is 22 mm, a slightly higher pull-out is achieved with a welding depth of 46 mm. Kanazawa *et al.* (2005) studied the pull-out forces of welded depths of 15 and 30 mm. The test results showed that the pull-out forces of the joints welded to the depth of 30 mm were twice larger than that of 15 mm.

Cracking occurs when dowels are welded to greater depths. In order to reduce welding errors, O'Loinsigh *et al.* (2012) soaked the dowels in sunflower oil. They joined two wooden beams with dowels by welding. The strength of the beams depends on the number of welded dowels. Hence, it is demonstrated that efficiency increases with increasing number of dowels. However, beyond a certain number of dowels, the incremental increase in beam strength is reduced until such point as it becomes negligible, as evidenced by the similar efficiencies achieved for the beams with 56 and 44 dowels.

The goal of this work was to determine at which depth of the welded beech wood dowels will achieve the highest strength by friction welding, and not the highest pull-out force. Namely, it is logical that the pull-out force increases with the increase of welding depth, but increasing depth also increases the dowels tip wear off area. Therefore, it is to expect that after a certain depth of welding, the strength of the joint will decrease.

EXPERIMENTAL

Materials

Common beech (*Fagus sylvatica* L.) wood planks required for the testing were bought from a commercial stock of unknown Croatian origin. The planks selected for this research were 50 mm thick, with the equilibrium water content of 11 ± 1% chosen from an air dried stack, without knots, pin knots, irregular heartwood, or cracks. When making and preparing samples (bases for welding), the following techniques were used: sawing, planing, fine cross sawing to final dimensions and drilling receiver holes on samples (bases) for dowel welding. All bases had approximately similar radial-tangential texture.

For wooden dowels production, beech wood grooved rods 1000 mm long and 10 mm in diameter were bought from the Schachermayer d.o.o., Zagreb, Croatia. The samples thus prepared (Fig. 1 and 2) were kept for 30 days in laboratory conditions (temperature of 23 ± 2 °C, relative air humidity of 55 ± 5%).

Specimens for Bases and Dowels Preparation

The base specimens were produced by sawing, fine planing, and cross-cutting, with a rectangular cross section of 30 × 30 ± 0.1 mm and a length of 64 ± 0.1 mm. These samples were used as a base for welding the dowels parallel to the grain. A hole was drilled in longitudinal direction in the center of each specimen (Fig. 1). Specimens with a rectangular cross section of 30 × 30 ± 0.1 mm and a length of 200 ± 0.1 mm were used as a base for welding the dowels perpendicular to the grain. In each specimen, three holes were drilled perpendicular to the grain, spaced 66 mm apart, and the two side holes were positioned away from the edge of the specimen by 34 mm (Fig. 2). The spiral drill was 8.1 mm in diameter, with a rotation frequency of 1520 min^{-1}. The diameters of the holes drilled parallel to the grain were smaller than the diameter of the drill by 0.01 to 0.05 mm; the diameter of the holes perpendicular to the grain were by 0.06 to 0.1 mm smaller than the diameter of the drill.

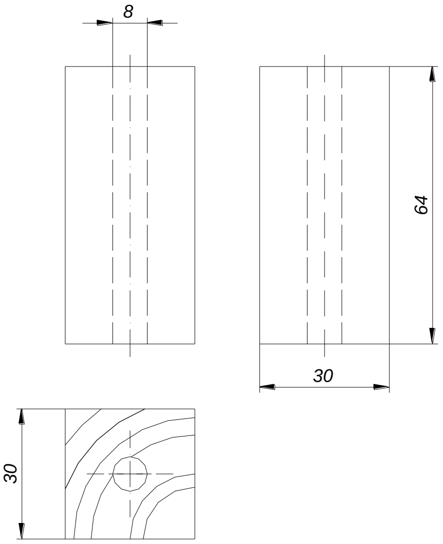

Fig. 1. Specimen (base) for welding the dowel parallel to the grain

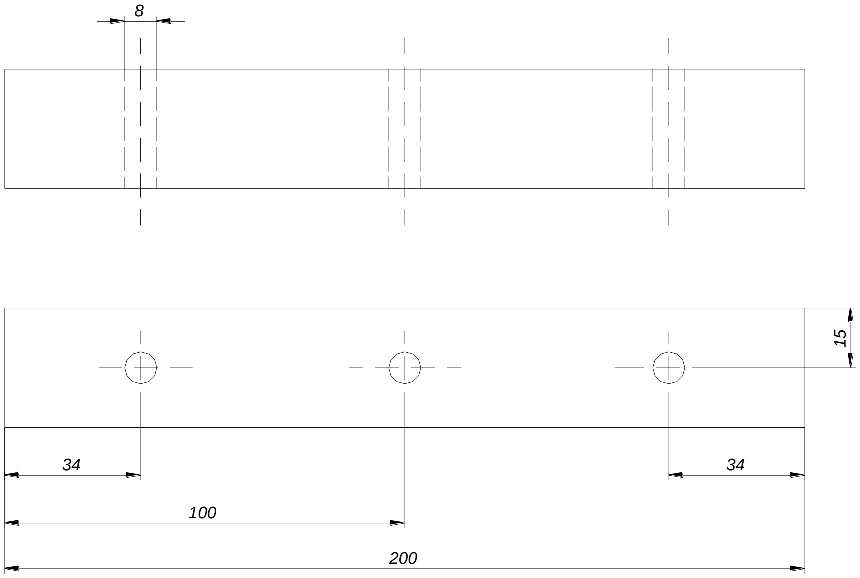

Fig. 2. Specimen (base) for welding the dowels perpendicular to the grain

The dowels were made by sawing 1000 mm long wooden rods to 120 mm. Each dowel end (cross section) was beveled for 1 mm at an angle of 45°. The average diameter of the grooved dowels was 10.06 mm measured crosswise at the top of the dowel. The dowels prepared in this way were equilibrated under laboratory conditions for more than 30 days before welding.

Determination of Water Content and Sample Density

After production, the samples were equilibrated under laboratory conditions for 30 days (temperature of 23 ± 2 °C, relative air humidity of 55 ± 5%). After this time in the climate chamber, the water content and density were determined. The average water content (according to HRN ISO 13061-1 (2015)) of beech samples was 9.15% (the minimum water content was 8.85%, and the maximum water content was 9.53%), the average density (according to HRN ISO 13061-2 (2015)) was 0.680 g/cm³ (the minimum density was 0.672 g/cm³, and the maximum was 0.693 g/cm³).

Production of Test Joints by Rotary Welding

All welded joints were made using the rotary welding technique, where the dowel rotates at a certain frequency, and was welded into a stationary base. The dowels were welded parallel (PV) and perpendicular to the wood grain (RTV). The rotation frequency of the dowels was 1520 min^{-1}, the welding depth was 15, 20, 25 and 30 mm, and the duration of welding was from 0.7 to 1.1 s (Table 1). Rotary welding was performed with an average interference fit of 2 mm. After the rotation was stopped, the pressure on the dowel was maintained for 5 seconds. In the case of PV samples, two dowels were welded to each base (one dowel on each side of the hole), and in the case of RTV samples, three dowels are welded to each base (Fig. 3).

Table 1. Data on Welding Parameters

Sample designation	Welding depth (mm)	Average duration of welding (s)	Feed per revolution (mm)
1,5 PV_x	15	0.7	0.85
2,0 PV_x	20	0.8	0.99
2,5 PV_x	25	0.9	1.10
3,0 PV_x	30	1.1	1.08
1,5 RTV_x	15	0.7	0.85
2,0 RTV_x	20	0.8	0.99
2,5 RTV_x	25	0.9	1.10
3,0 RTV_x	30	1.1	1.08

PV - welding in the direction of the wood grain
RTV - welding perpendicular to the direction of the wood grain
x- indicates the ordinal number of the welded dowel (1 through 30)

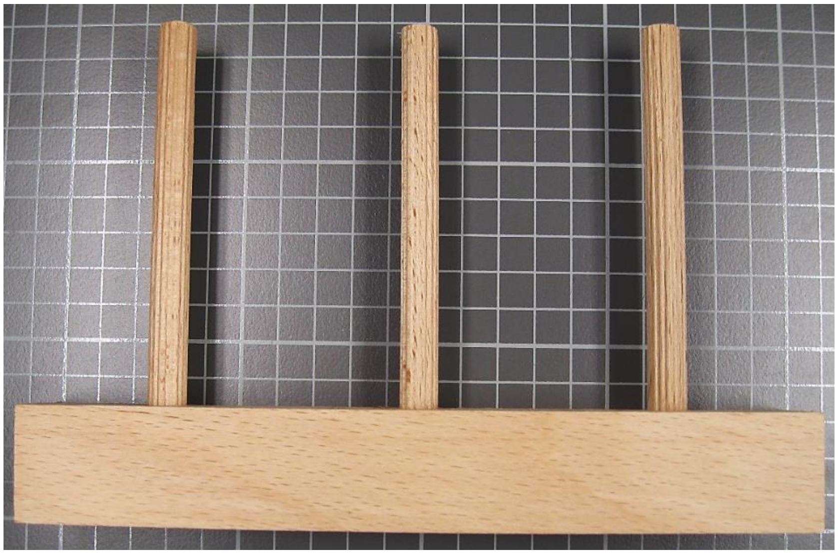

Fig. 3. Picture of the real specimen (dowels welded into the base) prepared for testing

After welding the PV samples, their bases were cut in half with use of a fine cross-cut saw. In this way two specimens (joints) from one base were obtained for testing. A total of 240 specimens were welded, and 228 were used in the research. In 12 specimens cracking in the base or of the dowels occurred, so they were not usable for further testing.

Measurement of Dowel Wear During Welding

All changes in dimensions of the dowel were measured using the ATOS measuring system (GOM GmbH Germany, Topomatika d.o.o. Zagreb). A total of 13 wear measurements were performed for each welding depth. ATOS is a mobile optical measuring device based on the principle of triangulation. It projects patterns of parallel lines onto the measuring object and records them using two digital cameras. For each individual pixel in the cameras, the three-dimensional coordinates of the corresponding point on the recorded surface are determined with high precision. This creates a polygonised network that describes the shape of the digitized object in detail.

Measuring (reference) points were glued to the dowel, and it was optically recorded. After that, the welding procedure was carried out, in such a way that the dowel was removed from the joint (when it reached the specified welding depth) during the rotation (solidification of the melt did not occur). An optical scan was made again, the images before and after welding were overlapped, and data were obtained on the wear and tear of the dowel during welding.

Testing Method and Data Analysis

The testing of the undamaged welded joints was carried out on a universal tensile testing machine after its visual control. All prepared joints were conditioned for seven days before they were tested on a computer controlled universal / tensile testing machine Otto Wolpert – Werke GmbH, Ludwigshafen, Germany. The joints were tested using joint jaws for precise positioning. The movement of jaws during the test was 5 mm/min. Maximum tensile force (pull-out force) has been recorded directly into computer.

The joint strength was calculated as the ratio of the measured pull-out force and the welded surface of each welding depth (Eq. 1),

$$\sigma = \frac{F}{A} (N/mm^2) \tag{1}$$

where σ is tensile strength of the welded joint (N/mm^2), F is the measured pull-out force (maximal tensile force; N), and A is the average welded surface of 13 measurements of each welding depth (mm^2).

The pull-out forces obtained from the measurements and calculated joints strengths were processed in the StatSoft Statistica 8.0 software package (StatSoft Europe, Hamburg, Germany). If the conditions of normality of distribution and homogeneity of variance were satisfied, the differences between individual groups of samples were tested by Student's T-test or by analysis of variance. If the condition of homogeneity of variance was not met; F-test and Levene's test, the Mann-Whitney U-test or the Kruskal-Wallis test was used to confirm whether or not there is a statistically significant difference between individual groups of samples. Post-hoc tests established a statistically significant differences between individual groups of samples if they existed (Tables 5 and 8). The differences greater than 5% was considered significant. Presentations of comparisons were made using box and whisker graphs.

RESULTS AND DISCUSSION

The influence of the welding depth is one of the important factors of welding the dowel parallel to the wood grain as well as perpendicular to the wood grain (Table 2 and Fig. 4). There was a statistically significant difference in pull-out force between the welding of the dowels at a depth of 15 and 20 mm in PV and RTV samples (Table 4). With an increase in the welding depth from 15 mm to 30 mm, a constant increase in pull-out force was recorded for PV and RTV samples (Fig. 4).

At a welding depth of 15 mm, the welded joint was formed, but due to the small welding depth, low pull-out forces were achieved. It is to be expected that with an increase in the welding depth over 20 mm, the pull-out force also increases significantly, which was not the case in this research (Fig. 4). The reason for this is the extreme wear of the tip of the dowel with the increase in welding depth. According to Zhu *et al.* 2017, the pull-out force increases up to a welding depth of 40 mm and then decreases slightly. As the welding depth increases, the duration of welding also increases. In this research, the welding time was extended or reduced in such a way that the displacement of the dowel per revolution was within the limits of the optimum determined in previous research (Župčić *et al.* 2011). According to previous research results of Župčić *et al.* (2011), the optimal welding time is when the feed is not less than 1 mm per revolution (welding depth 20 mm, difference between the diameter of the dowel and the hole 2 mm). With the reduction of the feed per revolution and the extension of the welding duration, the pull-out force decreases, but the statistically significant decrease of pull-out force was achieved when the welding duration was more than 1.5 s (Župčić *et al.* 2011). When the dowel is welded to a welding depth greater than 20 mm, the top of the dowel is worn off and not welded. When the top of the dowel has decreased in diameter, such that it is less than that of the hole, then there will be no friction between the dowel and the hole, so there is no welding thread. Therefore, a conical hole or a hole of different diameters (from larger diameter to smaller) should be used when welding the dowel at greater depths. Then the tip of the dowel would have an optimal distance between its diameter and the diameter of the hole.

Based on the results of the research, an increase in pull-out force was recorded in PV samples compared to RTV samples, which is not completely in line with the research results of Kanazawa *et al.* (2005) and Bo-Han *et al.* (2022). The mentioned authors worked with different welding parameters (greater difference in the diameter of the dowel and the hole, different duration of welding, frequency of rotation and modification of the dowel in order to increase the pull-out force). According to Bo-Han *et al.* (2022) the main difference with respect to the insertion direction is the optimum depth of the hole.

Table 2. Descriptive Statistics of the Pull-out Force Depending on Grain Orientation and Welding Depth

Code	Number of welded and tested joints	Mean pull out force (N)	Std. Dev (N)	Min (N)	Max (N)
1,5 PV	30	3326.5	457.4	2204	4037
2,0 PV	30	4638.4	575.1	3181	5696
2,5 PV	29	4718.2	358.8	3728	5276
3,0 PV	28	5024.8	405.3	4414	5849
1,5 RTV	28	2233.6	490.8	1330	3145
2,0 RTV	30	4128.4	359.3	3275	4996
2,5 RTV	27	4507.6	570.6	3091	5446
3,0 RTV	26	4928.3	547.5	3843	5879

Table 3. Levene Test of Homogeneity of Variances of the Pull-out Force

Variable	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
Pull-out	1018449	7	145492.7	1703638	220	77438.09	1.878827	0.074141
Marked effect are significant at p < 0.0500								

Table 4. Multiple Post Hoc Test (Pull-Out Force)

Code	Scheffe test; Maked differences are significant at p < 0.05000							
	(1) M=3326.5	(2) M=4638.4	(3) M=4718.2	(4) M=5024.8	(5) M=2233.6	(6) M=4128.4	(7) M=4507.6	(8) M=4928.3
1,5 PV (1)		0.000000	0.000000	0.000000	0.000000	0.000002	0.000000	0.000000
2,0 PV (2)	0.000000		0.999694	0.222911	0.000000	0.019102	0.993407	0.640723
2,5 PV (3)	0.000000	0.999694		0.552706	0.000000	0.002785	0.907286	0.912870
3,0 PV (4)	0.000000	0.222911	0.552706		0.000000	0.000000	0.026875	0.999202
1,5 RTV (5)	0.000000	0.000000	0.000000	0.000000		0.000000	0.000000	0.000000
2,0 RTV (6)	0.000002	0.019102	0.002785	0.000000	0.000000		0.257853	0.000006
2,5 RTV (7)	0.000000	0.993407	0.907286	0.026875	0.000000	0.257853		0.176861
3,0 RTV (8)	0.000000	0.640723	0.912870	0.999202	0.000000	0.000006	0.176861	

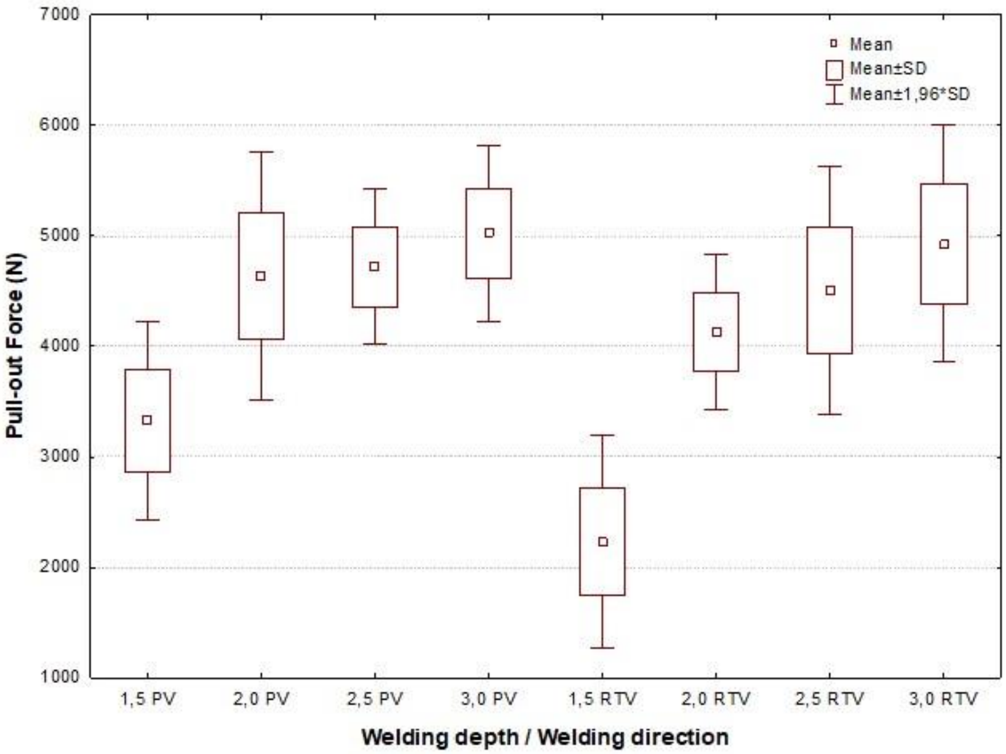

Fig. 4. Effect of welding depth and welding direction on pull-out force (welding direction parallel to the wood grain (PV) and welding perpendicular to the wood grain (RTV))

For the purpose of comparing the strength of the joint depending on the welding depth, an analysis of the wear off of the dowels' tips was made (Figs. 5 and 6). According to the research results, the diameter of the tip of the dowel is equal to the diameter of the hole at a welding depth of 20 mm. It follows from this that when the dowel is welded deeper than 20 mm, then the top of the dowel is not welded, but the slight increase in pull-out force is affected by the friction between the dowel and the wall of the hole. With a welding depth of 20 mm and 30 mm, the diameter of the dowels' top is approximately equal to the diameter of the hole, and therefore the top of the dowel is not welded. This is one of the main causes of the decrease in the strength of the welded joint as the welding depth increases.

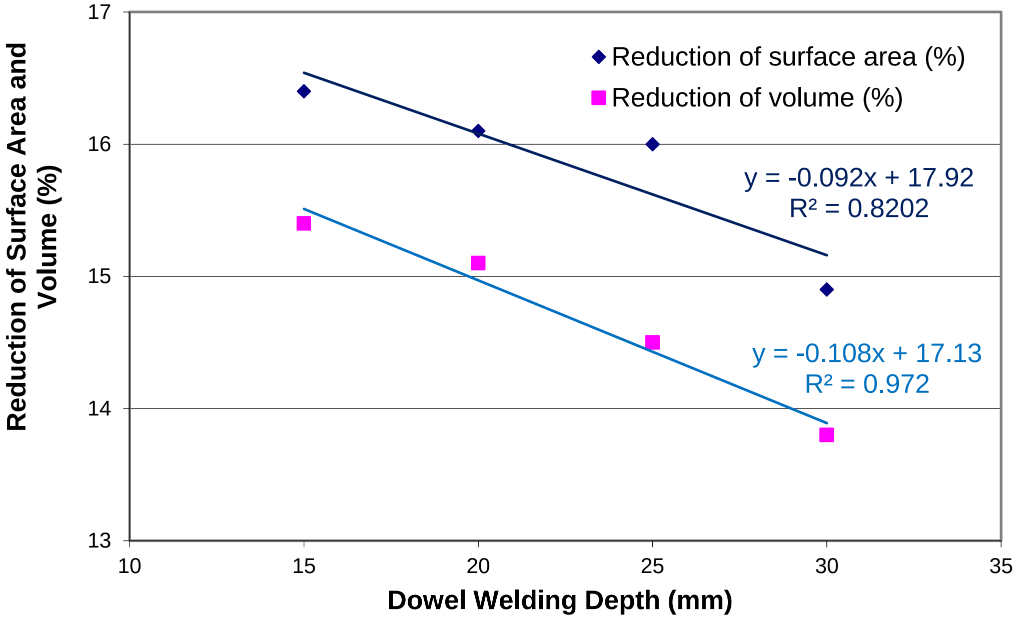

Fig. 5. Percentage reduction of the surface and volume of the dowel depending on the depth of welding

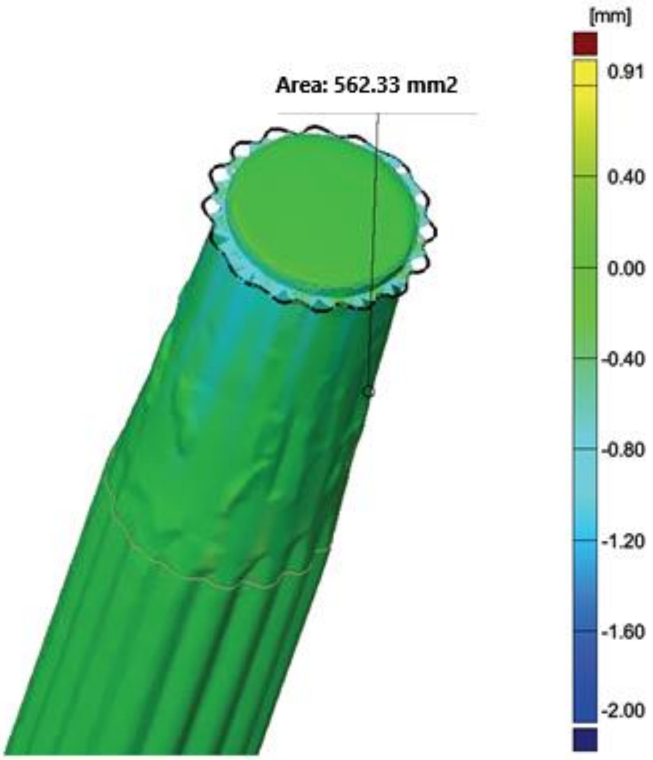

Fig. 6. 3D appearance of dowel spending during welding

The results of the research indicate that with a welding depth of 15 mm, the pull-out force is statistically significantly lower compared to other welding depths for PV and RTV specimens. If the strength of the joint is observed, then it is greater with a welding depth of 15 mm compared to the strength of the welded joint with a welding depth of 30 mm in PV specimens, while it is approximately the same in RTV specimens. The research results indicate that it is optimal to use a welding depth of 20 mm for PV and RTV specimens (the highest joint strength values are achieved). If the pull-out force is observed, then the welding depth of 30 mm achieves the highest values and it is certainly preferable to use it, even though the strength of the joint is the lowest. When increasing or decreasing the welding depth, the duration of the welding process should be taken into account (in relation to the welding depth of 20 mm) so that the displacement of the dowel is optimal.

The observed interval of the depth of welding of the dowel affects the increase of the pull-out force with its increase, while it affects the strength of the joint significantly differently (Tables 5 and 7, Fig. 7). An increase in joint strength was recorded (in the direction of the fibers it is not statistically significant, while it is statistically significant perpendicular to the fibers) with an increase in the welding depth from 15 to 20 mm (Table 7). A decrease in joint strength was recorded when the welding depth increased from 20 to 30 mm, and this was statistically significant for rods welded in the direction and perpendicular to the direction of the fibers (Fig. 7). The decrease in joint strength at welding depths greater than 20 mm is explained by the fact of intensive wear off of the dowels' top. This reduces the hole between the dowel and the hole, so the top of the dowel is not welded. In order for welding to take place at the top of the dowel, it is necessary to drill a conical hole or a hole of different diameters. The research shows that for welding depths of up to 20 mm, a cylindrical hole is optimal, and for greater welding depths, it is necessary to drill a hole of different diameter or a conical hole (recommend to investigate the influence of the shape of the hole).

Table 5. Descriptive Statistics of the Joint Strength Depending on Grain Orientation and Welding Depth

Code	Number of welded and tested joints	Means (N/mm^2)	Std. Dev (N/mm^2)	Min (N/mm^2)	Max (N/mm^2)	Q25 (N/mm^2)	Median (N/mm^2)	Q75 (N/mm^2)
1,5 PV	30	7.91	1.09	5.24	9.60	7.24	7.88	8.79
2,0 PV	30	8.28	1.03	5.68	10.17	7.57	8.47	9.14
2,5 PV	29	6.64	0.50	5.24	7.42	6.35	6.51	6.93
3,0 PV	28	5.90	0.48	5.19	6.87	5.53	5.75	6.25
1,5 RTV	28	5.31	1.17	3.16	7.48	4.53	5.34	6.30
2,0 RTV	30	7.37	0.64	5.84	8.91	7.10	7.43	7.73
2,5 RTV	27	6.34	0.80	4.35	7.66	5.90	6.44	6.88
3,0 RTV	26	5.79	0.64	4.52	6.91	5.46	5.82	6.28

Table 6. Levene Test of Homogeneity of Variances of the Joint Strength

Variable	SS Effect	df Effect	MS Effect	SS Error	df Error	MS Error	F	p
Strength	10.08763	7	1.441089	51.53570	220	0.234253	6.151846	0.000001
Marked effect are significant at $p < 0.0500$								

Table 7. Multiple Comparisons of Ranks (Joint Strength)

Depend.: Joint Strength (N/mm^2)	Multiple Comparisons p Values (2-tailed) Kruskal-Wallis Test: H (7. N=228) = 140.8798 p = 0.000							
	1,5 PV R:174.57	2,0 PV R:188.05	2,5 PV R:112.62	3.0 PV R:62.39	1,5 RTV R:48.79	2.0 RTV R:157.52	2,5 RTV R:96.11	3,0 RTV R:58.77
1,5 PV		1.000000	0.008699	0.000000	0.000000	1.000000	0.000205	0.000000
2,0 PV	1.000000		0.000316	0.000000	0.000000	1.000000	0.000004	0.000000
2,5 PV	0.008699	0.000316		0.113478	0.007268	0.250830	1.000000	0.070129
3,0 PV	0.000000	0.000000	0.113478		1.000000	0.000001	1.000000	1.000000
1,5 RTV	0.000000	0.000000	0.007268	1.000000		0.000000	0.218803	1.000000
2,0 RTV	1.000000	1.000000	0.250830	0.000001	0.000000		0.012581	0.000001
2,5 RTV	0.000205	0.000004	1.000000	1.000000	0.218803	0.012581		1.000000
3,0 RTV	0.000000	0.000000	0.070129	1.000000	1.000000	0.000001	1.000000	

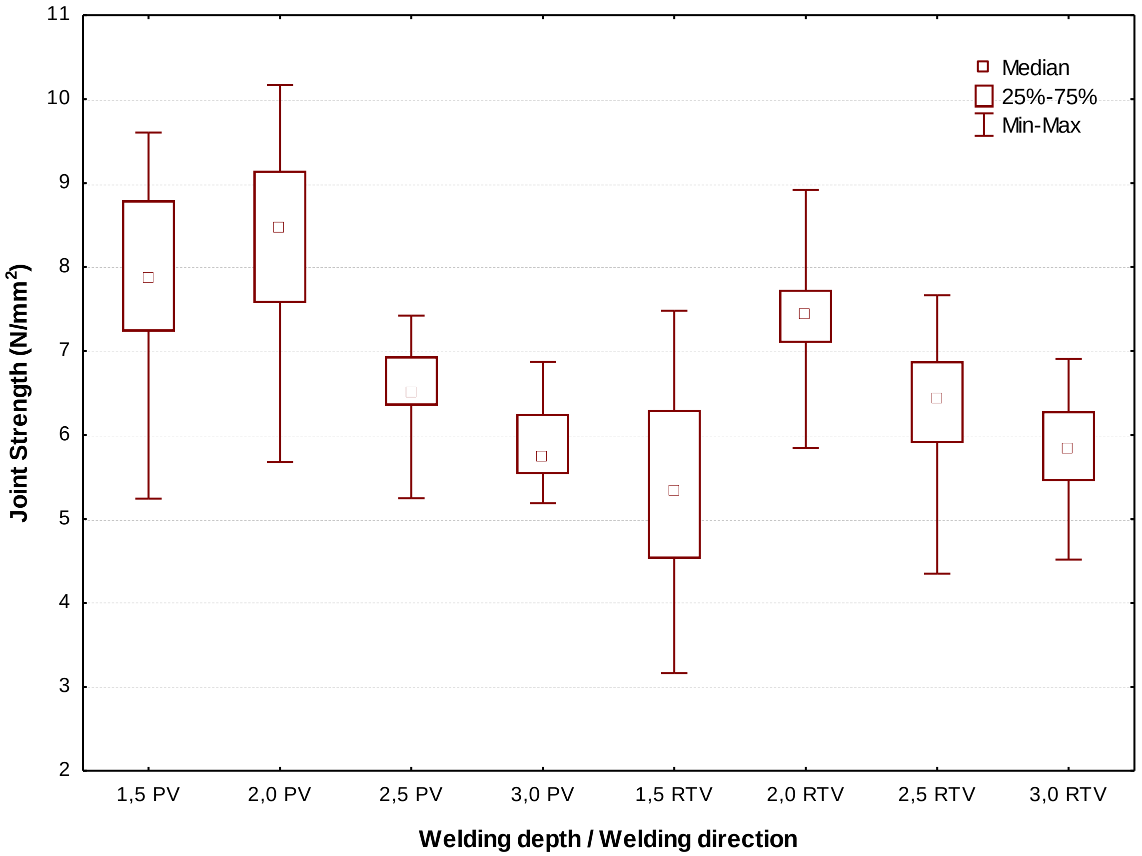

Fig. 7. Effect of welding depth on joint strength (welding direction parallel to the wood grain (PV) and welding perpendicular to the wood grain (RTV))

CONCLUSIONS

1. The depth of welding of the dowel is an important factor in rotary welding. It affects the pull-out force or the strength of the welded joint.
2. Welding the dowel parallel to the wood grain achieves higher values of pull-out force and joint strength compared to welding the dowel perpendicular to the wood grain.

3. An increase in pull-out force was recorded with an increase in welding depth (by 5 mm) from 15 mm to 30 mm. In the direction parallel to the grain, the increase in pull-out force is 50%, and in the direction perpendicular to the wood grain, the increase in pull-out force is greater than 100%.
4. The strength of the welded joint increases with the increase of the welding depth up to 20 mm (it reaches the maximum value for researched parameters of welding) and then decreases towards the welding depth of 30 mm. It turns out that 20 mm is the optimal welding depth for a cylindrical hole (for researched parameters of welding), although the optimal depth also depends on the difference between the dowel and hole diameter. As the welding depth increases from 20 to 30 mm in the direction parallel to the wood grain, the strength decreases by 28%, and in the direction perpendicular to wood grain, the strength decreases by 21%.
5. If the dowel joint in a construction is loaded only with tensile force, then the highest pull-out force is achieved with a welding depth of 30 mm (PV and RTV), so the use of the mentioned depth when welding the dowel parallel and perpendicular to the wood grain is justified.

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