Quantitative Evaluation of Rotational Wood Welding Joint Strength Based on Regression of Data Sets

Yun Xu,[a] Xuejiao Wang,[b,*] Aleksandr G. Chernykh,[c] Roshchina I. Svetlana,[d] Pavel S. Koval,[c] Egor V. Danilov,[c] and Anatoly Y. Naichuk[e]

This study aimed to enhance rotational wood welding technology by developing a simplified prediction model for pull-out strength. The key findings can offer a robust evaluation framework to advance rotational wood welding and expand its applications in woodworking. For instance, (1) A comprehensive database of 689 previously published trials was curated to identify key factors: substrate diameter, effective welded length, and substrate density. (2) Comparative analysis of test outcomes and predictive models revealed consistent trends, suggesting that modeling techniques for self-tapping wood screws could be applied to rotational wood welding joints. (3) Univariate linear regression validated the primary factors, leading to a multivariate model for predicting withdrawal capacity. Theoretical predictions closely matched empirical data, highlighting the model's industrial applicability.

DOI: 10.15376/biores.20.2.2933-2948

Keywords: Rotational wood welding; Performance Evaluation; Pull-out strength; Influential factor; Multivariate linear regression analysis

Contact information: a: School of Civil Engineering and Communication, North China University of Water Resources and Electric Power, Zhengzhou, 450045, China; b: School of International Education, Zhengzhou Railway Vocational and Technical College, Zhengzhou, 451460, China; c: Faculty of Civil Engineering, Saint Petersburg State University of Architecture and Civil Engineering, Saint Petersburg, 190005, Russia; d: Institute of Architecture Construction and Energy Engineering, Vladimir State University named after Alexander and Nikolay Stoletovs, 87 Gorky Street, Vladimir, 600000, Russia; e: Faculty of Civil Engineering, Brest State Technical University, Brest, 224023, Belarus;
** Corresponding author: wangxj151719@126.com*

INTRODUCTION

Wood welding technologies, encompassing linear vibration and rotational wood welding, represent significant advancements within the wood industry (Ebner *et al*. 2014). These methods employ high-frequency vibrations and rapid rotational movements to generate frictional heat, triggering chemical and physical transformations. This process causes the wood at the interface to melt and soften. Upon solidification, the melted material forms a robust solid phase that securely bonds disparate wooden components.

The mechanical integrity of joints produced *via* rotational wood welding, particularly under tensile stress, has been the subject of extensive research (Zupcic *et al.* 2014). Reinforcement strategies for these joints have also been explored. Notably, Pizzi *et al.* (2004) found that the strength of welds created through this method can rival that of traditional PVAc adhesives. Furthermore, preheating the wood to temperatures around 100 °C before welding has been shown to enhance the tensile strength of the joints beyond that achieved with PVAc bonding. This emerging technology has the potential to revolutionize the industry by providing a viable substitute for petrochemical-based adhesives, potentially leading to significant cost savings in future wood product manufacturing.

Numerous studies have explored the factors affecting the tensile strength of wood welded joints in civil engineering. Key variables include wood moisture content, rotational speed, grain orientation, dowel and predrilled hole dimensions, and additives such as ethylene-glycol (Costa Viana *et al.* 2023; Zhu *et al.* 2023; Zhong *et al.* 2024). Kanazawa *et al.* (2005) highlighted the importance of the diameter difference between the dowel and the predrilled hole, finding that minimal differences maximize welding strength. Belleville *et al.* (2013) identified wood species and rotational speed as crucial for peak temperature at the contact interface, influencing welding strength. Ebner *et al.* (2014) noted that tensile strength varies with the operational mode of automated wood welding machinery. Zupcic *et al.* (2014) found a significant correlation between wood species, welding direction, and welding strength. A welding depth of 30 mm for dowels loaded by tensile force was recommended by Zupcic *et al.* (2024). Leban *et al.* (2008) showed that increased rotational speed and insertion rate could reduce welding strength due to material expulsion from the interface. Recent research by Zhu *et al.* (2017) revealed that weld depth and $CuCl_2$ pretreatment of dowels enhance joint withdrawal capacity. Dowels immersed in $CuCl_2$ for 30 minutes showed superior tensile strength, especially at a 30 mm weld depth. Biological pretreatment of dowels significantly increased pull-out force after 4 weeks, but not after 2 weeks. Grooved dowels increased pull-out force by 26.9%, compared to 21.1% for smooth dowels (Zupcic *et al.* 2023b). Despite extensive research over the past two decades, identifying the primary factors influencing rotational wood welding strength remains challenging, hindering technological advancement and broader application of this technique.

The calculation model of glued-in-rod has been validated to predict the withdrawal strength of welded joints, with rotational speed, a critical variable, expressed through a trigonometric function based on Zhu *et al.* (2017). However, Belleville *et al.* (2013) identified species and rotational speed as the sole parameters influencing peak temperature and tensile strength at the welded line. Notably, 39% of studies focused on the 1500 to 2000 rpm range, where the maximal pull-out force was also observed (Xu *et al.* 2022). Thus, it can be inferred that for the withdrawal strength of welded joints, rotational speed may be a fixed variable. Failure to achieve a specific rotational speed could hinder the high densification of bonded interfaces, suggesting that the validated model may not comprehensively describe the physical process of rotational wood welding (Xu *et al.* 2022). Xu and Wang (2024) investigated the elastic deformation of rotational wood-dowel welding joints using the variational method. The findings indicated that the elastic solution method could accurately estimate the ultimate pull-out bearing capacity and deformation characteristics of the welding joints. This study represents a significant attempt to elucidate the physical process of rotational wood welding from the perspective of elastic deformation. It is noteworthy that the fabrication processes of rotational wood welding and self-tapping wood screws have some similar aspects. Compared to the glued-in-rod calculation model, the strength calculation model for self-tapping wood screws may better predict the tensile strength of welding joints from both physical and theoretical perspectives.

Wood friction welding, utilizing high-speed rotation, presents a promising avenue for producing eco-friendly and cost-effective wooden products without relying on adhesives. Recent studies have delved into the analysis of axially-loaded dowel-welded wood joints, providing a wealth of experimental data to elucidate the interplay between various factors and the tensile strength of the welding joints. To date, only a couple of predictive models, proposed by Zhu *et al.* (2017) and Ganne-Chedeville *et al.* (2005), respectively, have been put forward to estimate the optimal withdrawal capacity of these joints. However, the limited sample sizes in these studies have precluded the development of a robust assessment framework. This study aimed to compile a comprehensive database of pull-out test results from existing literature and develop a multivariate predictive model to accurately assess the tensile strength of welding joints. The research was expected to significantly advance this emerging technology, facilitating its application in timber structure construction and furniture manufacturing. However, a potential limitation is the presence of systematic differences across datasets, which may introduce variability and affect the accuracy of the analysis. Despite this, the approach offers the potential for a robust fit with minimal error. The primary objective is to evaluate the feasibility of achieving a robust data fit across multiple studies, aiming to establish a foundational relationship for global research applications. For clarity, a flow chart detailing the proposed solution is presented in Fig. 1.

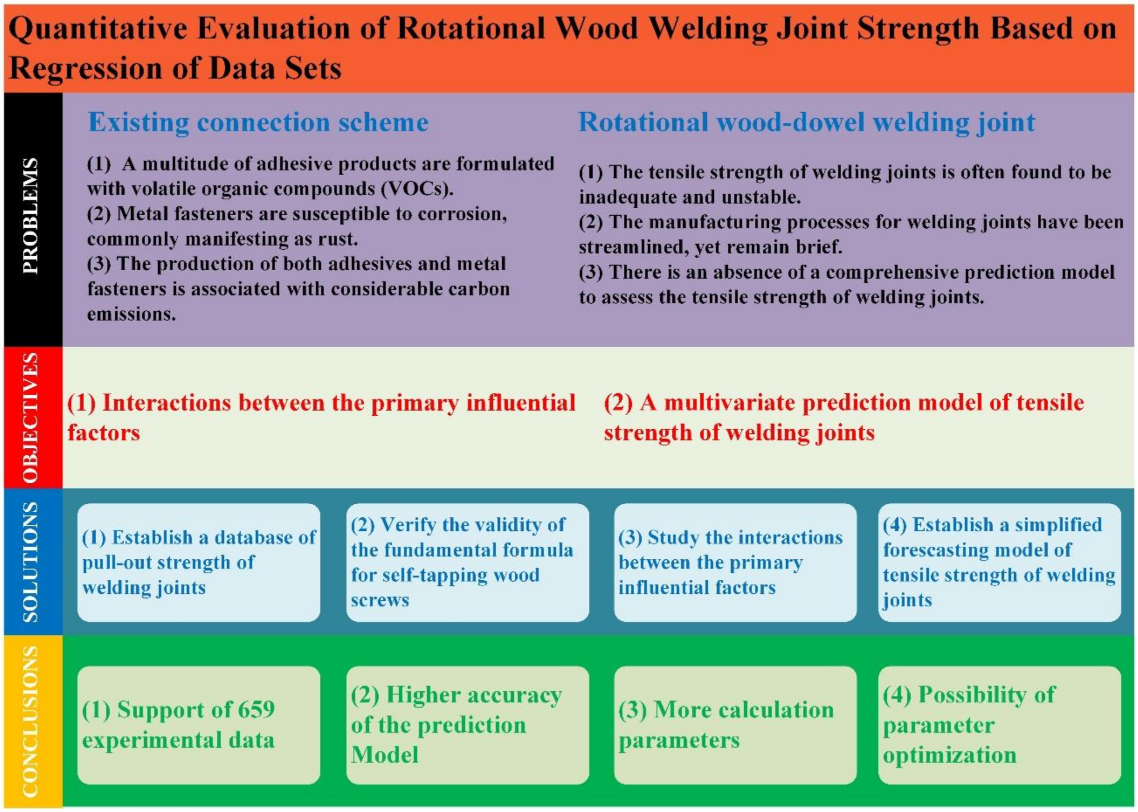


Fig. 1. Flowchart of the solution scheme

EXPERIMENTAL

Theoretical Approach

Figure 2 schematically depicts the axially-loaded dowel-welded wood joint, comprising: (a) a wood dowel rotationally welded into a substrate with a predrilled hole; (b) the fusion of the bonding interface during welding; (c) the pull-out test setup. The figure annotates various parameters as follows: L denotes the total length of the wood dowel, L_{eff} signifies the effective welded length, L_{out} represents the remaining length of the dowel, α

is the angle between the insertion direction and the grain orientation of the substrate, D is the initial diameter of the dowel, d is the diameter of the predrilled hole in the substrate, P stands for the welding force, and F is the pull-out force. Previous research (Pizzi *et al.* 2004; Ganne-Chedeville *et al.* 2005) has demonstrated that rotational wood welding shares similar characteristics and material alterations with linear welding. According to Cornuault and Carpentier (2020), the rotational wood welding process can be distilled into three distinct phases, taking into account the contact-boundary conditions between the dowel and the substrate: (i) initial boundary contact, where the wood samples' moisture content is the predominant factor influencing joint withdrawal capacity; (ii) boundary collapse, characterized by friction-induced heat that catalyzes the release of lignin and the creation of welded spots; (iii) boundary fusion, during which the molten material flows and solidifies to form a durable adhesive bond upon cooling.

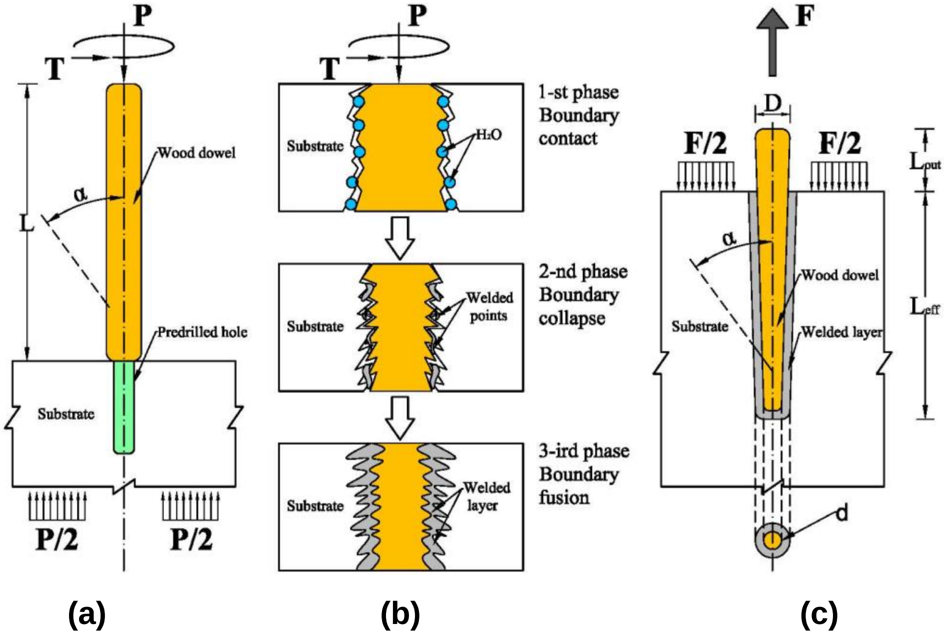


Fig. 2. Schematic representation of the axially-loaded dowel-welded wood joint: (a) Wood dowel rotation welded in the substrate with a predrilled hole; (b) Welding fusion of bonding interface; (c) Pull-out test

Figure 2 elucidates the parallels between the fabrication processes of dowel-welded wood joints and the operational mechanics of self-tapping wood screws. In contemporary timber construction, self-tapping screws serve as pivotal load-bearing elements, both directly and indirectly, thereby optimizing the efficacy of fasteners and joints while concurrently curtailing expenses. The withdrawal capacity of these screws within timber is known to be contingent upon a spectrum of factors, including moisture content, ambient temperature, wood density, screw tip geometry, orientation relative to the wood grain, pre-drilling practices, and the insertion depth of partially threaded screws. Table 1 compiles a comprehensive array of parameters gleaned from prevailing standards and scholarly research that inform predictive models for self-tapping wood screws. Equation 1, as delineated in Table 1, is the foundational formula endorsed by a majority of research papers and normative documents. The equation considers the effective threaded length of the screw (L_{eff}), the wood density (ρ), and the screw diameter (d) as the principal variables influencing the model. It is noteworthy that there is a marked disparity in the coefficients

(*A*, *B*, *C*, and *D*) across different codes and studies. Moreover, it is the withdrawal capacity of screws aligned perpendicular to the wood grain that is typically referenced as the standard measure. The calculation is as follows,

$$F_{ax,90} = A \cdot d^{B} \cdot {L_{eff}}^{C} \cdot \rho^{D} \tag{1}$$

where $F_{ax,90}$ is the withdrawal capacity of self-tapping screw perpendicular to the grain of substrate (N), d is the screw diameter (mm), L_{eff} is the effective threaded length of the self-tapping screw (mm), ρ is the substrate density (kg/m^3), and *A*, *B*, C, and *D* are undetermined coefficients.

Table 1. Overview: Parameters of Current Codes and Research for $F_{ax,90}$

Model	Source Documents	A	B	C	D
1	Code: ÖNORM EN 1995-1-1	0.52	0.5	0.9	0.8
2	Code: DIN 1052:2008	70×10^{-6}	1	1	2
3	Code: SIA 265:2003D	75×10^{-3}	0.8	0.8	1
5	Code: GB 50005-2017	$133.648\times10^{-1.5}$	1.75	1	1.5
6	SNIP 64.13330.2011	0.3×π	1	1	0
7	BlaS and Uibel (2009)	31	0.8	0.9	
8	BlaS and Uibel (2007)	1.398	1.77	1.91	0.75
		1.367	1.08	1.91	0.75

The research conducted by Pizzi *et al.* (2004) revealed that within a certain rotational speed range, the angle of welding direction relative to the grain orientation of the substrate, as well as the surface texture of the dowels (whether rough or smooth), did not significantly affect the welding outcome. Building on this insight, this paper posited that the predictive methodology employed for self-tapping wood screws can be equally applicable to welding joints. This assumption was grounded in the adoption of the foundational equation, Eq. 1, as a model. Consequently, the primary factors influencing welding joints have been identified as distinct from those affecting self-tapping wood screws, specifically highlighting wood density, the difference in diameter between the wood dowel and the predrilled hole, and the effective welded length. In contrast, Yin *et al.* (2022) highlighted that the welding speed and the moisture content of the wood substantially influenced the interfacial force and the temperature at the welding interface. In an effort to streamline the computation of the withdrawal capacity for welding joints, this paper proposes four working hypotheses, analogous to the modeling strategy for self-tapping wood screws:

- The welding parameters, such as rotational speed and holding pressure duration, have been optimized.
- The high-speed rotation ensures a uniform welded layer along the bonding interfaces.
- The difference in grain orientation between the dowel and the substrate has been disregarded.
- The size effect of the substrate has been ignored.
- The impact of wood moisture content has been neglected.

Experimental Database

In this study, a comprehensive database was compiled from 659 trials documented in previous research, as referenced in Table 2, to analyze rotational wood welding joints.

Table 2. Overview: Parameters and Pull-out Test Results

Group	Dowel				Substrate			F (N)
	Species	D (mm)	L_{eff} (mm)	Inserted direction	Species	Density (kg/m^3)	d (mm)	
A-1	Chinese Birch	10	40	Perpendicular	Eastern Larch	595	8	2966
A-2	Chinese Birch	12	30	Perpendicular	Eastern Larch	595	9.5	2712
A-3	Chinese Birch	12	30	Perpendicular	European Spruce	450	8.5	1856
B-1	European Beech	10.04	20	Parallel	European Beech	680	8	6280
B-2	European Beech	10.04	20	Parallel	European Oak	690	8	5190
B-3	European Beech	10.04	20	Parallel	European Spruce	450	8	2220
B-4	European Beech	10.04	20	Perpendicular	European Beech	710	8	5330
B-5	European Beech	10.04	20	Perpendicular	European Oak	690	8	4850
B-6	European Beech	10.04	20	Perpendicular	European Spruce	450	8	3650
B-7	European Beech	10.04	20	Perpendicular	European Beech	710	8	5750
B-8	European Beech	10.04	20	Perpendicular	European Oak	690	8	4990
B-9	European Beech	10.04	20	Perpendicular	European Spruce	450	8	2240
B-10	European Beech	10.04	20	Perpendicular	European Beech	710	8	5540
B-11	European Beech	10.04	20	Perpendicular	European Oak	690	8	4610
B-12	European Beech	10.04	20	Perpendicular	European Spruce	450	8	4200
C-1	European Beech	10	20	Parallel	European Beech	710	9	2265
C-2	European Beech	10	20	Parallel	European Beech	710	9	2288
C-3	European Beech	10	20	Parallel	European Beech	710	9	2417
C-4	European Beech	10	20	Parallel	European Beech	710	9	1197
D-1	Yellow Birch	9.68	25	Perpendicular	Sugar Maple	705	7.67	6804
D-2	Yellow Birch	9.68	25	Perpendicular	Sugar Maple	705	7.67	5961
D-3	Sugar Maple	9.68	25	Perpendicular	Yellow Birch	690	7.67	3613
D-4	Sugar Maple	9.68	25	Perpendicular	Yellow Birch	690	7.67	4275
E-1	European Beech	10	15	Perpendicular	European Beech	710	8	3184

Notes: Group A-1 from the work (Zhu *et al.* 2017), and Group A-2/3 from the work (Zhang *et al.* 2017); Group B from the work (Zupcic *et al.* 2014); Group C from the work (Ebner *et al.* 2014); Group D from the work (Belleville *et al.* 2013); Group E from (Ganne-Chedeville *et al.* 2005).

The standard practice in the field involves inserting a wood dowel into a substrate *via* a pre-drilled hole, utilizing either a high-speed manual or a benchtop drilling machine. This is followed by a pull-out test performed with a universal testing machine. To ensure the reliability of the data, 20 sets were meticulously selected as representative samples from the 659 trials, corroborated by established online databases (Green *et al.* 1999; Meier 2007; European Wood 2011; MatWeb 2011). Table 2 summarizes the parameters and outcomes of the pull-out tests, detailing dowel diameters ranging from 8 to 12 mm, predrilled hole diameters from 7.67 to 9 mm, effective welded lengths between 15 to 40 mm, the orientation angle relative to the substrate grain (perpendicular or parallel), the densities of both dowel and substrate, and the peak pull-out forces observed (F_{max}).

The types of wood dowels utilized in the trials included:

- ø 10 mm/60 mm, ø 10.04 mm/120 mm, and ø10 mm/80 mm dowel of European beech (*Fagus sylvatica*);
- ø 10 mm/100 mm and ø 12 mm/100 mm dowel of Chinese birch (*Betula*);
- ø 9.68 mm/82 mm dowel of yellow birch (*Betula alleghaniensis*);
- ø 9.68 mm/82 mm dowel of sugar maple (*Acer saccharum*);

The following types of substrates were used:

- 50 mm×50 mm×20 mm substrate of European beech (*Fagus sylvatica*);
- 30 mm×30 mm×200 mm substrate of European beech (*Fagus sylvatica*);
- 30 mm×30 mm×200 mm substrate of European oak (*Quercus petraea*);
- 30 mm×30 mm×200 mm and 60 mm×60 mm × 40 mm substrate of European spruce (*Picea abies*);
- 40 mm×50 mm×500 mm and 60 mm×60 mm × 40 mm substrate of Eastern larch (*Larix laricina*);
- 30 mm×30 mm×400 mm substrate of sugar maple (*Acer saccharum*);
- 30 mm×30 mm×400 mm substrate of yellow birch (*Betula alleghaniensis*);

RESULTS AND DISCUSSION

Comparison Between the Measured and Calculated Values

This paper integrated equations from prevailing standards and recent studies, as outlined in Table 1, to predict the withdrawal capacity of rotational wood welding joints, utilizing the empirical data from Table 2. The juxtaposition of measured versus predicted values, depicted in Fig. 3, reveals a significant discrepancy, suggesting that the current equations may not precisely forecast the experimental outcomes (indicated by the red line).

Nonetheless, the envelope diagram (highlighted in green) demonstrates that Eq. 1, which is based on the foundational formula from existing codes and research, can approximate the trend of the pull-out test results from Table 2. This observation suggests that the basic structure of Eq. 1, commonly used for self-tapping screws, might be extendable to wood dowels. The four working hypotheses presented in the section above appeared to hold merit. Moreover, it is recommended that wood density, the relative diameter difference between the dowel and the predrilled hole, and the effective welded length should be regarded as the principal factors in the modeling of welding joints.

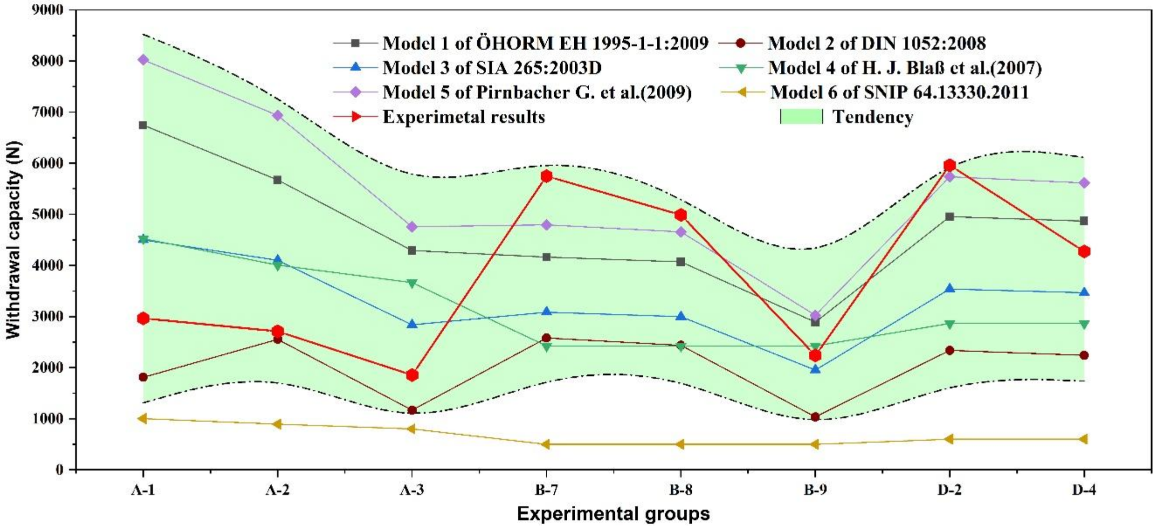


Fig. 3. Comparison between the calculated values obtained from the prediction models (refer to Table 1) and the measured values provided in Table 2

Influence of Wood Moisture Content on the Withdrawal Capacity of Welding Joints

The interactions between parameters that are crucial in wood dowel welding through high-speed rotation have been evaluated by Ganne-Chedeville *et al.* (2005). Among these, the interplay between rotation rate and dowel moisture content emerged as the most significant, with a descending order of importance. Rotary friction welding of heat-treated Scotch pine is feasible, and the joint strength exceeds that of glued and hammered joints (Zhang *et al.* 2024). Li *et al.* (2023) found that the dry bonding strength and the wet bonding strength (after immersion in cold, hot, and boiling water) of pretreated dowels were higher than those without pretreatment and significantly superior to traditional polyvinyl acetate (PVAc) adhesive bonding. Biwôlé *et al.* (2023) investigated the cold water resistance of welded joints in Iroko wood (*Milicia excelsa* C. C. Berg) and identified water-insensitive oligomers as key to their water resistance. Thermal modification can enhance the dimensional stability of wood by reducing its hygroscopicity, but it can also cause cracks, affecting welding strength. Adjusting welding parameters can prevent cracks but may reduce pull-out strength by more than 25%. Citric acid treatment of wood and dowels significantly reduces pull-out strength, questioning its use in wood welding (Župčić *et al.* 2023a). For the commercial wood dowels, an equilibrium moisture content of 12% has been widely accepted in scientific and industrial contexts. Therefore, once the most determinant factor from previous studies was controlled, the most impactful factors were identified as the welding depth, wood species, the dowel/hole diameter difference.

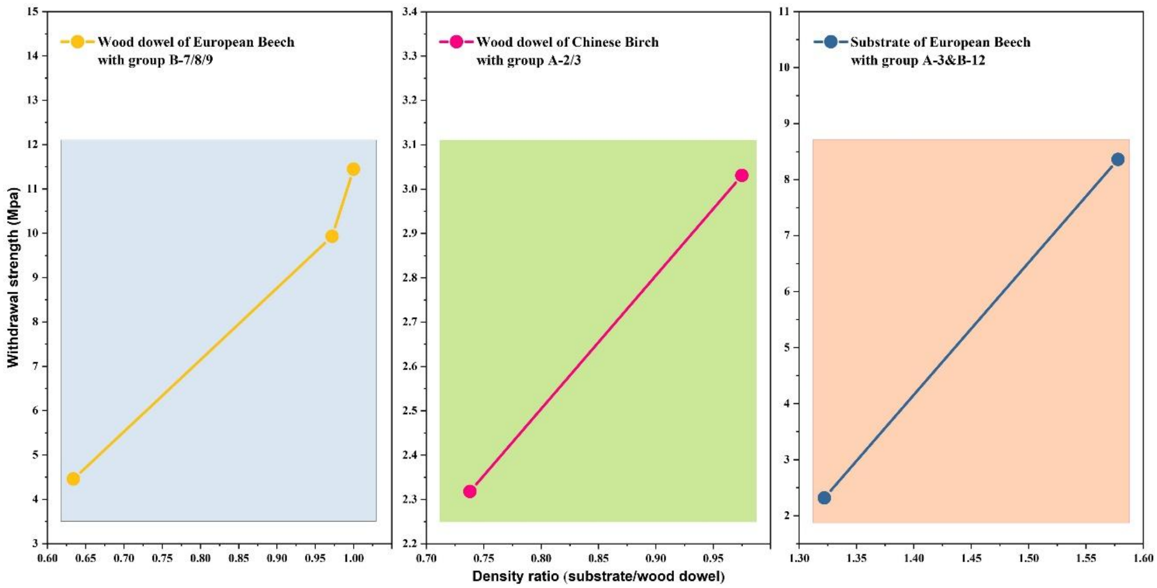
Influence of Diameters on the Withdrawal Capacity of Welding Joints

The study of Pizzi *et al.* (2004) demonstrated that the relative diameter difference between the wood dowel and the predrilled hole was the primary factor impacting on the withdrawal capacity of welding joints. While the relative diameter difference was considered a major factor, other influential parameters could also enhance joint strength (Kanazawa *et al.* 2005). In line with existing literature, the findings of Pizzi *et al.* (2004) indicated that a dowel diameter of 10 mm and a predrilled hole diameter of 8 mm yielded optimal results. Another study (Rodriguez *et al.* 2010) suggested that a dowel/hole diameter ratio of 5/4 (*i.e.*, 1.25) was the optimal ratio, with no significant differences observed for higher ratios under the same conditions. Table 2 shows that the range of dowel/predrilled hole diameter ratios falls between 1.11 and 1.41. It is worth noting that a ratio of 1.26 has been accepted by 79% of the test groups, supporting the findings of work (Rodriguez *et al.* 2010). While the diameter ratio is important for evaluating the withdrawal capacity of welded joints, previous studies have not established a uniform reference. Given the complex interactions among different factors, it is hard to believe that a ratio of 1.26 will be the optimal value under all conditions. Considering future standardization in design and manufacture, if the dowel diameter remains constant and the diameter ratio is restricted within limited ranges, the predrilled hole diameter will have a greater impact on welding strength than the wood dowel.

The research by Pizzi *et al.* (2004) highlighted the significance of the relative diameter difference between the wood dowel and the predrilled hole as a key determinant of the withdrawal capacity of welding joints. Although this diameter difference is a crucial factor, Kanazawa *et al.* (2005) identified additional parameters that could further enhance joint strength. Consistent with these findings, a dowel diameter of 10 mm and a predrilled hole diameter of 8 mm were found to be optimal. Rodriguez *et al.* (2010) proposed an ideal dowel/hole diameter ratio of 5/4 (1.25), with negligible variance observed for higher ratios under identical conditions. According to Table 2, the observed range of dowel to predrilled hole diameter ratios spans from 1.11 to 1.41, with a ratio of 1.26 being prevalent in 79% of the test groups, corroborating the conclusions of Rodriguez *et al.* (2010). While the diameter ratio is a critical metric for assessing the withdrawal capacity of welded joints, there is no consensus on a standard reference value across previous studies. The intricate interplay of various factors suggested that a ratio of 1.26 might not universally represent the optimal value. In anticipation of future standardization in design and manufacturing, maintaining a constant dowel diameter and limiting the diameter ratio within a specific range implies that the predrilled hole diameter can exert a more pronounced influence on the welding strength than the dowel itself.

Influence of Species on the Withdrawal Capacity of Welding Joints

In comparison to linear vibrational welding, studies by Kanazawa *et al.* (2005) and Gfeller *et al.* (2003) have shown that rotational wood welding could induce the formation of furanic compounds at elevated temperatures. Notably, the concentration of these compounds was found to be lower on the wood dowel than on the substrate. Further research by Zupcic (2010) revealed that the density of the wood, even within the same species but at varying densities, could significantly bolster the strength of the welded joints. This suggested a direct, positive relationship between the tensile strength of the weld and the density of the substrate, especially when using denser wood species. To corroborate the influence of wood density, three test cases from Table 2 are graphically represented in Fig. 4, where the density ratio between the dowel and the substrate is the variable of interest. For a constant dowel density, an increase in substrate density leads to stronger welds, as shown in Fig. 4(a) and 4(b). Conversely, maintaining a consistent substrate density while increasing the dowel density also enhances the joint strength, as indicated in Fig. 4(c). Although dowels can be fashioned from various wood types, beech wood has been recommended by Zupcic *et al.* (2014) as the optimal material, with the grain orientation of the dowel being a negligible factor. Therefore, it can be deduced that when beech wood is employed for the dowel, the substrate density emerges as a more pivotal factor influencing the welding strength.



(a) (b) (c)

Fig. 4. The influence of the density ratio on the withdrawal strength of welded joints. (a) The influence of density ratio (substrate/wood dowel) on the withdrawal strength of joints or the wood dowel of European beech with group B-7/8/9. (b) The influence of density ratio (substrate/wood dowel) on the withdrawal strength of joints for the wood dowel of Chinese birch with group A-2/3. (c) The influence of density ratio (wood dowel/substrate) on the withdrawal strength of joints for the substrate of European beech with group A-3&B-12.

Pearson Correlation Analysis

To evaluate the impact of key factors such as predrilled hole diameter, welded length, and substrate density on the tensile strength of wood welding, Table 3 showcases the Pearson correlation analysis used to investigate the relationship between the withdrawal capacity of welded joints and various influencing factors. The analysis indicated that the effective welded length of the dowel correlated with a coefficient of -0.64, suggesting a notable inverse relationship with withdrawal capacity. Additionally, the dowel diameter had a correlation coefficient of -0.32, and the diameter of the predrilled hole in the substrate had a coefficient of -0.52, both indicating negative correlations with withdrawal capacity. While the effective welded length of the dowel showed a stronger correlation with withdrawal capacity than the other factors, the diameter of the predrilled hole was identified as having a more significant impact on the welding strength, particularly when the dowel diameter and diameter ratio were held constant. Conversely, the substrate density exhibited a positive correlation with withdrawal capacity, marked by a coefficient of 0.68. It is crucial to recognize that a univariate linear regression model is insufficient to capture the withdrawal capacity of welded joints based solely on these factors. As such, a multivariate linear regression model is recommended to more accurately reflect the complex interplay among these variables.

Table 3. Pearson Correlation Analysis

Parameter	A	B	C	D	E
A	1	0.36	-0.42	0.91	-0.64
B	0.36	1	-0.15	0.27	-0.32
C	-0.42	-0.15	1	-0.3	0.68
D	0.91	0.27	-0.3	1	-0.52
E	-0.64	-0.32	0.68	-0.52	1

Notes: Pearson correlation analysis conducted to examine the relationship between the withdrawal capacity of the welded joints and other factors. A is denoted as the dowel diameter. B is denoted as the effective welded length of dowel. C is denoted as the substrate density. D is denoted as the diameter of the predrilled hole in substrate. E is denoted as the Withdrawal capacity of welding joints perpendicular to the grain of the substrate.

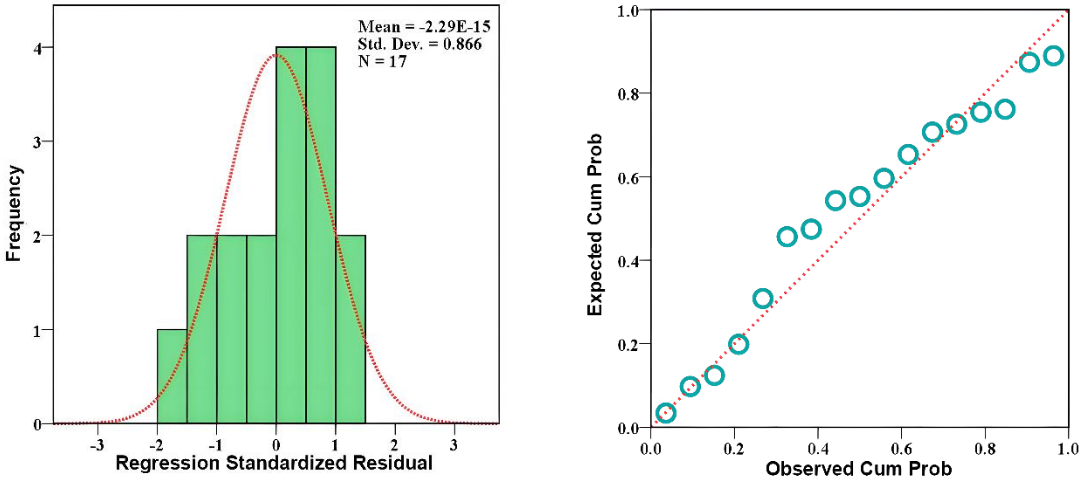
Multivariate Linear Regression Analysis

The histogram of the dependent variable log10 ($F_{ax,90}$) in Fig. 5(a) suggested that the standardized residuals of the regression adhere to a normal distribution, with a mean close to zero (μ=-2.29E-15) and a standard deviation near one (σ=0.866). Figure 5(b) shows the data points dispersed around the diagonal line within the first quadrant, reinforcing the normal distribution assumption for the residuals.

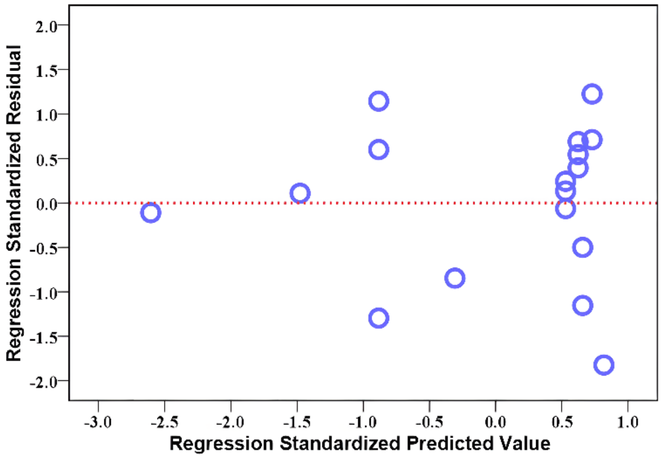
Figure 5(c) depicts the residuals forming a consistent "horizontal band" around the zero line, lacking any apparent pattern or variability in relation to the predicted values, thus indicating homoscedasticity.

Table 4 presents Variance Inflation Factor (VIF) values below 10 for each independent variable, signifying no substantial multicollinearity. After verifying the linear regression assumptions, it is evident that the collected data met the criteria for normality, linearity, homoscedasticity, and the absence of multicollinearity, making it suitable for multiple linear regression modeling.

Building on the analysis of the primary factors and their influence on welding strength, the prediction model incorporated the predrilled hole diameter, welded length, and substrate density. To derive a multivariate linear relationship, a logarithmic transformation was applied to both sides of Eq. 1, yielding Eq. 2. Subsequent multivariate linear regression analysis, based on test results perpendicular to the grain of the substrate (referenced in Table 2), formulated the prediction model for the withdrawal capacity of rotational wood welding joints as Eq. 3.



(a) (b)



(c)

Fig. 5. Condition verification of the multivariate linear regression analysis. (a) Histogram of the regression standardized residual of the dependent variable $\mathbf{log_{10}}(\boldsymbol{F_{ax,90}})$. (b) Normal P-P plot of the regression standardized residual of the dependent variable $\mathbf{log_{10}}(\boldsymbol{F_{ax,90}})$. (c) Residuals versus predicted values of the dependent variable $\mathbf{log_{10}}(\boldsymbol{F_{ax,90}})$.

Table 4. Check of Multicollinearity

Model	Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Collinearity Statistics	
	B	Std. Error	Beta			Tolerance	VIF
$\log_{10}(L_{eff})$	-0.158	0.308	-0.099	-0.976	0.348	0.846	1.182
$\log_{10}(d)$	0.947	0.380	0.495	-0.514	0.616	0.795	1.258
$\log_{10}(\rho)$	0.528	3.160	0.073	2.490	0.028	0.166	6.029

The model coefficient of determination, R^2, is notably high at 0.966, signifying its robust predictive accuracy for the variations observed in the dataset.

$$\log{}_{10}^{(F_{ax,90})} = log_{10}^{(A)} + B \cdot log_{10}^{(d)} + C \cdot log_{10}^{(L_{eff})} + D \cdot log_{10}^{(\rho)} \tag{2}$$

$$F_{ax,90} = 9.827 \cdot 10^{-1.259} \cdot d^{-1.121} \cdot {L_{eff}}^{-0.388} \cdot \rho^{1.934} \tag{3}$$

To ascertain the precision of Eq. 3, the data from Table 2 was bifurcated into two categories: (i) the first type, encompassing 17 groups derived from pull-out tests executed perpendicular to the substrate’s grain, and (ii) the second type, consisting of 3 groups from tests conducted parallel to the grain (Note: these were not included in the original model data). Figure 6 juxtaposes the empirical values from Table 2 with those calculated *via* Eq. 3. The figure revealed that for the first type, deviations range from a minimum of 0.61% to a maximum of 14.44%, with an average deviation of 5.55%. For the second type, the deviations spanned from a minimum of 0.28% to a maximum of 14.36%, averaging at 5.50%. Prior studies (Pizzi *et al.* 2004; Zupcic *et al.* 2014) have established that the welding strength is not significantly affected by the angle between the welding direction and the grain orientation. Thus, the proposed model is adept at predicting the withdrawal capacity for joints welded both perpendicular and parallel to the grain. It must be noted, however, that this study was not without its limitations. While the primary factors were considered, the new prediction model did not account for the relationship between welding strength and other potential factors, due to a lack of extensive research. Nonetheless, the proposed model (with R^2=0.966) demonstrated sufficient accuracy to enhance product optimization within the timber structure and furniture industries. For further validation of Eq. 3, additional data from pull-out tests conducted parallel to the grain is necessary.

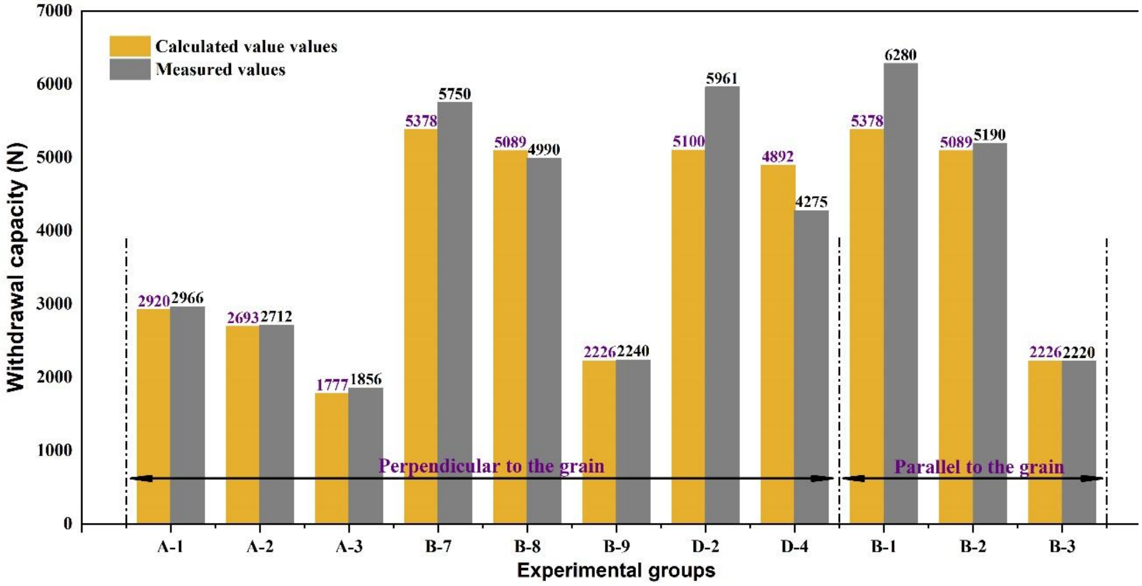


Fig. 6. Comparison between the measured values presented in Table 2 and the calculated values derived using the prediction model defined by Eq. 3.

CONCLUSIONS

1. A robust database comprising 689 trials was curated from existing literature to facilitate data analysis and modeling for pull-out tests. Through examination of the experimental data, pivotal factors were pinpointed: substrate diameter, effective welded length, and substrate density. These elements formed the cornerstone for predicting the withdrawal capacity of rotational wood welding joints.
2. A comparative analysis of the test outcomes detailed in Table 2 against the calculated values derived from various predictive approaches (as outlined in Table 1) revealed congruent trends across all models, barring SNIP 64.13330.2011. Given the analogous manufacturing processes and mechanical behaviors of both joint types, it was posited that the modeling techniques employed for self-tapping wood screws might be transferable to rotational wood welding joints.
3. The study utilized univariate linear regression analysis to validate the three primary factors integral to the prediction model. Leveraging the modeling strategies associated with self-tapping wood screws and the insights from linear regression analysis, a multivariate model, expressed as Eq. 3, was introduced for forecasting the withdrawal capacity of rotational wood welding joints. The theoretical predictions of the proposed model aligned closely with empirical measurements, underscoring its robust correlation and potential applicability in industry settings.

ACKNOWLEDGMENTS

The authors thank Professor Chernykh A.G. of Saint Petersburg State University of Architecture and Civil Engineering, Professor Naichuk A.Y. of Brest State Technical University, and Professor Svetlana R.I. of Vladimir State University named after Alexander and Nikolay Stoletovs for their contribution in the critical discussion of the manuscript. The authors gratefully acknowledge the financial support from the Research Project of Colleges and Universities in Henan Province (grant no. 23A560007), Henan Provincial Natural Science Foundation (grant no. 242300420037), Training Program for Young Backbone Teachers of Undergraduate Colleges and Universities in Henan Province (grant no. 2023GGJS075), Research Project of Science and Technology Plan of Henan Province Housing and Urban-Rural Construction (grant no. K-2336), National Foreign Expert Individual Projects (grant no. S20240101).

REFERENCES CITED

Belleville, B., Stevanovic, T., Cloutier, A., Pizzi, A., Salenikovich, A., and Blanchet, P. (2013). "Production and properties of wood-welded panels made from two Canadian hardwoods," *Wood Science and Technology* 47(5), 1005-1018. DOI: 10.1007/s00226-013-0554-7

Biwôlé, J. J. E., Biwolé, A. B., Mfomo, J. Z., Pizzi, A., Segovia, C., Abessolo, D., Ndiwe, B., Fongnzossie, E. F., Ateba, A., and Meausoone, P.-J. (2023). "Iroko wood (*Milicia excelsa* CC berg), a good candidate for high-speed rotation-induced wood dowel welding: An assessment of its welding potential and the water resistance of its welded joints," *International Journal of Adhesion and Adhesives* 123, article 103360. DOI: 10.1016/j.ijadhadh.2023.103360

Biwôlé, J. J. E., Biwolé, A. B., Pizzi, A., Mfomo, J. Z., Segovia, C., Ateba, A., Fongnzossie, E. F., Ouertani, S., Chen, X., Ndiwe, B., *et al.* (2023). "A review of the advances made in improving the durability of welded wood against water in light of the results of African tropical woods welding," *Journal of Renewable Materials* 11(3). DOI: 10.32604/jrm.2023.024079

BlaS, H. J., and Uibel, T. (2007). "Tragfahigkeit von stiftformigen Verbindungsmitteln in Brettsperr-holz," Karlsruher Berichte zum Ingenieurholzbau, Band 8, Lehrstuhl fur Ingenieurholz-bau und Baukonstruktionen, Universitat Karlsruhe, Karlsruhe. DOI: 10.5445/KSP/1000006318

Blaß, H. J., and Uibel, T. (2009). "Bemessungsvorschläge für Verbindungsmittel in Brettsperrholz," *Bruderverlag Albert Bruder GmbH & Co. KG*, Karlsruhe 1-13. DOI: 10.5445/IR/1000010673

Cornuault, P., and Carpentier, L. (2020). "Tribological mechanisms involved in friction wood welding," *Tribology International* 141, article 105963. DOI: 10.1016/j.triboint.2019.105963.

Costa Viana, A. C., Dias de Moraes, P., and Weingaertner, W. L. (2023). "Evaluation of the interface of Eucalyptus specimens welded by rotary friction," *Maderas. Ciencia y tecnología* 25. DOI: 10.4067/s0718-221x2023000100426.

DIN 1052:2008-12. (2008). "Design of timber structures - General rules and rules for buildings," Germany Standard, Berlin.

Ebner, M., Petutschnigg, A., Schnabel, T., Sternad, B., Huskic, A., and Gaubinger, K.

(2014). “Development of an automated wood welding process,” *Journal of Adhesion Science and Technology* 28(18), 1783-1791. DOI: 10.1080/01694243.2014.922159

European Wood. (2011). “Mechanical Properties of Wood,” Wood-database, (https://www.europeanwood.org.cn).

Ganne-Chedeville, C., Pizzi, A., Thomas, A., Leban, J. M., Bocquet, J.-F., Despres, A., and Mansouri, H. (2005). “Parameter interactions in two-block welding and the wood nail concept in wood dowel welding,” *Adhesion Science and Technology* 19(13-14), 1157-1174. DOI: 10.1163/156856105774429037

GB 50005-2017 (2017). “Standard for design of timber structures,” Chinese Standard, Beijing.

Gfeller, B., Zanetti, M., Properzi, M., Pizzi, A., Pichelin, F., Lehmann, M., and Delmotte, L. (2003). “Wood bonding by vibrational welding,” *Journal of Adhesion Science and Technology* 17, 1573-89. DOI: 10.1163/156856103769207419

Green, D. W., Winandy, J. E., and Kretschmann, D. E. (1999). “Mechanical Properties of Wood, (https://www.fs.usda.gov/treesearch/pubs/7149).

Kanazawa, F., Pizzi, A., Properzi, M., Delmotte, L., and Pichelin, F. (2005). “Parameters influencing wood-dowel welding by high-speed rotation,” *Journal of Adhesion Science and Technology* 19(12), 1025-1038. DOI: 10.1163/156856105774382444

Leban, J.-M., Mansouri, H. R., Omrani, P., and Pizzi, A. (2008). “Dependence of dowel welding on rotation rate,” *Holz als Roh- und Werkstoff* 66, 241-242. DOI: 10.1007/s00107-008-0228-6

Li, S., He, J., Wu, J., Yang, Y., Sun, Q., Lu, X., and Zhang, Z. (2023). “Study on water resistance improvement of wood dowel rotation welding joints,” *Journal of Wood Chemistry and Technology* 43(4), 177-194. DOI: 10.1080/02773813.2023.2204858

MatWeb. (2011). “European Mechanical Properties of Wood. Wood-database, http://www.matweb.com.

Meier, E. (2007). “American Mechanical Properties of Wood. Wood-database, https://www.wood-database.com.

ÖNORM EN 1995-1-1. (2004). “Eurocode 5: Design of timber structures – Part 1-1: General – Common rules and rules for buildings. European Standard.

Pizzi, A., Leban, J.-M., Kanazawa, F., Properzi, M., and Pichelin, F. (2004). “Wood dowel bonding by high-speed rotation welding,” *Journal of Adhesion Science and Technology* 18(11), 1263-1278. DOI: 10.1163/1568561041588192

Rodriguez, G., Diouf, P., Blanchet, P., and Stevanovic, T. (2010). “Wood-dowel bonding by high-speed rotation welding — Application to two Canadian hardwood species,” *J. Adhes. Sci. Technol.* 24(8-10), 1423-1436. DOI: 10.1163/016942410X501025

SIA 265:2003D (2003). “Timber structures,” Swiss Standard.

SNIP 64.13330.2011 (2011). “Timber structures,” Russian Standard.

Xu, Y., and Wang, X. J. (2024). “Elastic deformation analysis of rotational wood-dowel welding joint system based on the variational method,” *Holzforschung* 78(7), 402-413. DOI: 10.1515/hf-2024-0003

Xu, Y., Gao, D. Y., and Chernykh, A. G. (2022). “Prediction model of axially-loaded wood-dowel welding joints by high-speed rotation,” *Holzforschung* 76, 544-555. DOI: 10.1515/hf-2024-0003

Yin, W., Lu, H., Zheng, Y., and Tian, Y. (2022). “Tribological properties of the rotary friction welding of wood,” *Tribology International* 167, 107396. DOI: 10.1016/j.triboint.2021.107396

Zhang, J., Fu, W., and Zhu, H. (2024). “Characterisation of rotary friction welding process and mechanism of heat-treated Scotch pine," *BioResources* 19(2), 3793. DOI: 10.15376/biores.19.2.3793-3807

Zhang, J. R., Gao, Y., Xu, L., Luo, X. Y., and Zhu, X. D. (2017). "Properties and mechanism of Larch with wood-dowel rotation welding," *Journal of Northwest Forestry University* 32(4), 229-234. DOI: 10.3969/j.issn.1001-7461.2017.04.38

Zhong, X., Li, D., Xu, X., Li, Q., Yu, D., Wu, Z., Liang, J., Peng, J., Gu, W., Zhao, X., *et al*. (2024). "Effects of dowel rotation welding conditions on connection performance for Chinese fir dimension lumbers," *Forests* 15(6), article 1038. DOI: 10.3390/f15061038

Zhu, X., Xue, Y., Qi, P., Lan, Q., Qian, L., Shen, J., Gao, Y., Li, J., Mei, C., and Li, S. (2023). "Flexural properties of wooden nail friction welding of laminated timber," *BioResources* 18(1), article 1166. DOI: 10.15376/biores.18.1.1166-1176

Zhu, X. D., Yi, S. L., Gao, Y., Zhang, J. R., Ni, C., and Luo, X. Y. (2017). "Influence of welded depth and CuCl2 pretreated dowels on wood dowel welding," *Journal of Wood Science* 63(5), 445-454. DOI: 10.1007/s10086-017-1644-1

Župcic, I. (2010). *Čimbenici koji utječu na spajanje bukovih tokarenih elemenata tehnikom zavarivanja*, Ph.D. Dissertation, University of Zagreb, Zagreb, Croatia.

Župčić, I., Đukić, I., and Hasan, M. (2024). "Influence of the depth of friction-welded dowels on the strength of rotary welded joints," *BioResources* 19(2), article 3047. DOI: 10.15376/biores.19.2.3047-3059

Župčić, I., Đukić, I., Jug, M., Jurišić, M., and Hasan, M. (2023a). "The influence of different wood modifications on pull-out force of rotary welded dowels," *Drvna Industrija* 74(1), 93-103. DOI: 10.5552/drvind.2023.008

Župčić, I., Šafran, B., and Hasan, M. (2023b). "Influence of biological pretreatment of wooden dowels on strength of rotary welded joints," *BioResources* 18(1), article 2100. DOI: 10.15376/biores.18.1.2100-2111

Zupcic, I., Vlaovic, Z., Domljan, D., and Grbac, I. (2014). "Influence of various wood species and cross-sections on strength of a dowel welding joint," *Drvna Industrija* 65(2), 121-127. DOI: 10.5552/drind.2014.1324

Article submitted: January 6, 2025; Peer review completed: February 14, 2025; Revised version received and accepted: February 17, 2025; Published: February 27, 2025.
DOI: 10.15376/biores.20.2.2933-2948