Influence of Biological Pretreatment of Wooden Dowels on Strength of Rotary Welded Joints

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Welding wood achieves joints whose strength is comparable with the strength of glued joints. When welding, the top of the dowel is not welded because of the lack of melted lignin. To achieve satisfactory strength of a welded joint, it is necessary to optimize the main welding factors such as interference fit, frequency of dowel rotation, welding depth, welding duration, *etc*. There are also other ideas to increase the strength of welded joints. One of these ideas involves pre-treatment of dowels with wood decaying fungi to increase the proportion of lignin on the surface of the dowels and thus in the melt. This paper presents the results of the impact of pretreatment of beech wood dowels with the brown-rot fungus *Gloeophyllum trabeum*. Results showed that biological pretreatment of the dowels had a significant impact on the pull-out force of the joint. Pretreatment for 4 weeks caused a substantial increase in pull-out force, while pretreatment for 2 weeks did not have a positive effect on the strength of the welded joint. Grooved dowels exhibited an increase in pull-out force of 26.9%, while smooth dowels had an increase of 21.1% of pull-out force. Research also determined additional vibrations during welding.

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INTRODUCTION

Through the welding of wood it is possible to join two or more wooden elements without the application of glue. It is a relatively new method based on friction between contact surfaces of wood. Friction is achieved by vibration or rotation, heat is created that softens and melts the chemical structure of wood (lignin and accessory substances), and cellulose fibres are intertwined in the melt thus formed. The strength of rotary welded joints is comparable to the strength of glued joints. Approximately 2 s after welding, the frictional force achieves a stable state. Normal force has been found to increase and then gradually decrease with respect to time after rotation is stopped (Yin *et al.* 2021). The strength of welded joints is affected by many factors such as duration of the welding process (movement of the dowel in the direction of the vertical axis per revolution), interference fit (difference between the diameter of the dowel and the hole), welding depth, rotation frequency, wood species, direction of welding (parallel or perpendicular to the direction of the fibres), width of growth rings, welding temperature (Pizzi *et al.* 2004; Bocquet *et al.* 2007; Leban *et al.* 2008; Župčić 2010; Župčić *et al.* 2022), *etc*. Natural additives, such as lignin and rosin, have been found to improve the welding properties (Placencia *et al.* 2015).

Thermally and chemically modified wooden samples (alcohol-based) during exposure to boiling water had greater pull-out force compared to untreated ones (Jones and Pizzi 2007). Improving the strength of the joint was achieved by welding dry and hot dowels (water content 1.5% and heated to 100 °C) into the substrate (Pizzi *et al.* 2004). Dowels dried to 1% moisture content and heated to 100 °C achieved 55% greater pull-out force than control dowels with 12% moisture content (Kanazawa *et al.* 2005). The same authors state that the cross-cutting of the tip of the dowels and the treatment of the dowels with ethylene glycol also increase the average pull-out force. The strength of the joint is increased by reducing the moisture content of the dowels from 12% to 0% at the rotation frequency of 1165 min^{-1} and 1515 min^{-1} (Ganne-Chedeville *et al.* 2005).

Preheating the beech samples before vibrational welding resulted in an increase in joint strength with increased preheating temperature, while oak samples experienced a decrease in joint strength with increased preheating temperature (Omrani *et al.* 2010). The reason for this may be in different mechanisms of welding of oak wood compared to welding mechanisms of other hardwoods (Properzi *et al.* 2005).

Thermally modified ash can be successfully friction welded or glued (Amirou *et al.* 2020). Thermal modification of wood affects the strength of the welded joints. According to research of Župčić *et al.* (2009), the pull-out force of rotary welded dowels in thermally modified hornbeam (*Carpinus betulus* L.) was 47% lower than the pull-out force of dowels welded in reference hornbeam base. The duration of the welding process in modified bases had to be longer than of welding in untreated ones because of the increased brittleness of modified wood. Thermal modification of beechwood has a negative impact on the pull-out force of rotary welded dowels (Župčić *et al.* 2011). The same authors noted that a higher modification temperature resulted in a greater decrease in the pull-out force of welded dowels. Thermal modification of beech wood at 180 °C reduced the pull-out force of welded dowels by almost 58% compared to pull-out force of unmodified samples. The pull-out force is reduced by an increase in mass loss caused by thermal modification. Thermal modification is not suitable for improving the resistance of the welded joint to the influence of water. The poor water resistance of welded joints is based on the uneven swelling of the welded joint, which causes strong stresses in the welded joint (Vaziri *et al.* 2019). Thermal modification in vibration welding affects a significant reduction in shear strength (Vaziri and Sandberg 2021). In vibration welding, the strength of the welded joint is twice that of unmodified wood (Boonstra *et al.* 2006).

Zhang *et al.* (2018) investigated the impact of treating the birch wood (*Betula pendula* Roth) dowels with $CuCl_2$ solution on welding temperature and pull-out force. Birch dowels were welded into the base of Chinese larch (*Larix gmelinii* Rupr.). Welding analysis showed that there was a significant nonlinear relationship between welding temperature, welding depth, and welding time. The test results also showed that the treated samples had more melt compared to untreated ones. Dowels treated with $CuCl_2$ with the welding duration of 3 s achieved 68% greater pull-out force than untreated dowels with the same welding time (Zhang *et al.* 2018).

During the welding process, intensive wear of the dowel occurs, and especially at its tip. A prerequisite for achieving greater joint strength involves the welding of the entire surface of the dowel, which is in contact with the base. Because of the intense wear of the tip of the dowel, the wood fibers are intertwined, and there is not enough lignin to bond them to each other. Therefore, the aim of this study is to biologically pre-treat wooden dowels with a lignicolous fungi that will increase the proportion of lignin in the surface layer of the dowels, so that during welding in the melt formed from the dowel there may be more lignin present that would result in better welding. Lignicolous brown-rot fungi break down the holocellulose part of the cell wall of the wood, thereby increasing the brittleness of wood, which can have a negative effect on the strength of the welded joint and dowel itself if fungal treatment takes too long.

EXPERIMENTAL

Specimens Preparation

The research was performed on beech wood (*Fagus sylvatica* L.) planks that were naturally dried to a moisture content of 13 ± 1%. Laths with a cross-section of 50 × 50 mm^2 and a length of 3 m were sawn from 50-mm-thick planks. Laths were conditioned for 60 days in an air-conditioning chamber (T = 23 ± 2 °C, φ = 55 ± 5%). Through fine planing, rectangular lattices with a cross-section of 30 × 30 ± 0.2 mm^2 and a length of 3 m were obtained. Fine transverse sawing provided elements of 30 × 30 × 300 ± 0.2 mm^2. All prepared elements had a similar radial-tangential texture, without knots, cracks, and visible mechanical damage, and were conditioned for next 30 days in the same air-conditioning chamber (T = 23 ± 2 °C, φ = 55 ± 5%) before drilling the welding holes and holes for temperature probes. Four holes for welding dowels were drilled with an 8-mm diameter spiral high-speed steel (HSS) drill, and four 3-mm diameter holes for temperature probes were drilled perpendicular to each welding hole (Fig. 1). After drilling the holes, and before welding the dowels, the prepared base elements were additionally conditioned in the specified climate for 3 weeks.

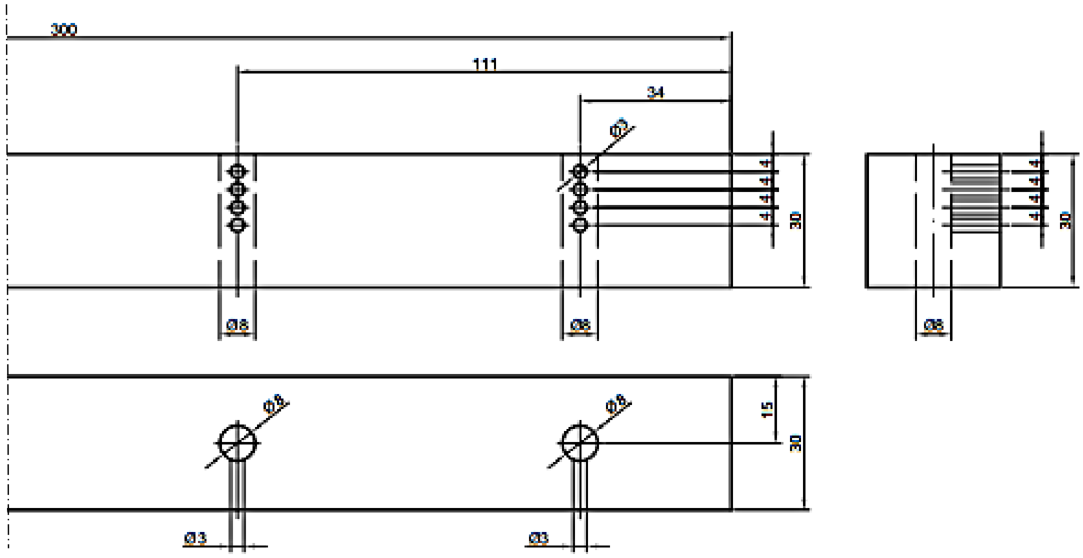

Fig. 1. Octagonal projection of the base element and the position of drilling holes for dowels and temperature probes (measures in mm)

The dowels used for welding were made of smooth and grooved beech wood rods 1000 mm long, and 10 mm in diameter purchased on the free market. For research purposes, the rods were shortened to a length of 120 mm. After cutting the dowels to the correct length, their edges were subsequently chamfered by 1.0 mm at a 45° angle to allow welding to start more easily. The dowels prepared in this way (without cracks and visible damage) were conditioned in laboratory conditions for 60 days (T = 23 ± 2 ° C, φ = 55 ± 5%). After conditioning, the dowels were biologically modified.

For biological modification of the dowels, *i.e.*, surface enrichment with lignin, using pure culture of the lignicolous brown-rot fungus *Gloeophyllum trabeum* (Pers.) Murrill was used. The method of preparation of the nutrient medium and the calculation of the mass loss of the dowel caused by fungus (MLF) were completed in accordance with HRN EN 113-2 (2021). Potato dextrose agar (PDA) manufactured by Biolife (Biolife Italiana S.r.l., Milan, Italy) was used as the nutrient medium for pure culture of fungal mycelium. All equipment, nutrient medium before mycelial inoculation, and dowels were autoclaved at 121 °C for 20 min. Inoculation of mycelium on a nutrient medium and exposure of the dowels to fungal mycelium were performed under sterile conditions. The cultivation of mycelium on a nutrient medium lasted 2 weeks in a mycological climate chamber (T = 23 ± 0.5 °C and φ = 75 ± 5%). Exposure of the dowels to the fungal mycelium was performed perpendicular to the surface of the nutrient medium (mycelium), with strict care that the dowel with its beveled tip barely touched the mycelium of the fungus (Fig. 2). Placing the dowels (specimens) perpendicular to the mycelium is not in accordance with HRN EN 113-2 (2021), but this way of placing the dowels above the mycelium resulted in a controlled action of the mycelium precisely in the part of the dowels that is necessary for welding.

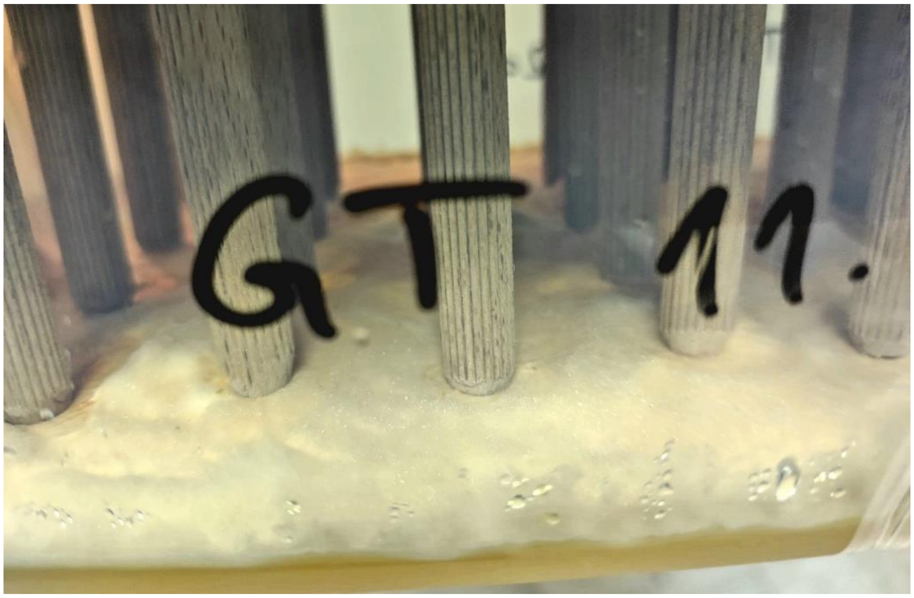

Fig. 2. Perpendicular positioning of grooved dowels over fungal mycelium

Incubation of the dowels over mycelium was completed in the mycological climate chamber for 2 and 4 weeks. A minimum incubation time of 2 weeks was selected by observing the development of mycelium when it overgrew the dowels up to a height of approximately 35 mm. Incubation of 4 weeks was chosen as a twice longer incubation time. From each group of dowels, 4 dowels were selected on which the mass loss caused by fungus degradation (MLF) was determined. Other dowels intended for welding were decontaminated in the oven dryer at temperatures of 30 and 45 ± 0.1 °C for 3 h each, and at a final temperature of 60 ± 0.1 °C for 1 h. This decontamination regime has been chosen not to cause fast drying, neither cracking nor twisting of the dowels, and it is also in accordance with the International Standards for Phytosanitary Measures No. 15 (ISPM 15 2019). After thermal decontamination, all dowels were air-conditioned in laboratory conditions for 3 weeks before welding.

Welding the dowels into the base elements was completed using a welding device that has the possibility of rotating the dowel and automatic movement in the direction of dowels longitudinal axis. Welding was performed by rotating the dowel with a constant rotation frequency of 1520 min^{-1} with a movement of the dowel along the longitudinal axis. Applying optimal duration of welding the dowel into base element of 1 s (Župčić 2010) resulted in many dowels cracks and welding errors; therefore, the second set of dowels was prepared. The duration of welding the dowel into the base element was prolonged to 5.2 s, and the pressure on the dowel after the rotation stopped lasted 3 s to 5 s. Using this regime of welding, all dowels were successfully welded. The average interference fit of smooth dowels was 2.10 mm, and that of the grooved ones was 2.05 mm. The depth of welding was 20 mm. Four dowels were welded in each base element. The base element in which the dowels were welded was static, and the welding direction of the dowels was perpendicular to the wood fibers direction. A total of 172 dowels were welded (Table 1).

Table 1. List of Labels Used and Description of Dowel Treatments

Specimen Label	Specimen Description
S C–x	Smooth dowels – control (x = 1-30)
S 1–x	Smooth dowels pre-treated with fungus, 2 weeks incubation (x = 1-28)
S 2–x	Smooth dowels pre-treated with fungus, 4 weeks incubation (x = 1-28)
G C–x	Grooved dowels – control (x = 1-30)
G 1–x	Grooved dowels pre-treated with fungus, 2 weeks incubation (x = 1-28)
G 2–x	Grooved dowels pre-treated with fungus, 4 weeks incubation (x = 1-28)
x – represents number of successfully welded dowel in each group	

The average moisture content of the base elements into which dowels were welded was 9.81 ± 0.28% (measured according to HRN ISO 13061-1 (2015)), and the average density was 0.678 ± 0.03 g/cm³ (according to HRN ISO 13061-2 (2015)).

Testing Method

The welded joints were conditioned for seven days before they were tested on a computer controlled universal / tensile testing machine Shimadzu AGX-V (AUTOGRAPH Precision Universal Tester AGX-V, SHIMADZU Corporation, Kyoto, Japan). The movement during the test was 5 mm/min. The joints were tested using joint jaws for precise positioning. No visible faults and no other damages were found on tested joints. To all tested groups of joints (Table 1), two smallest and two largest data of pull-out forces were rejected.

Data analysis

The data obtained from the measurements were processed in the StatSoft Statistica 8.0 software package (StatSoft Europe, Hamburg, Germany). In the case when the condition of normality of distribution and homogeneity of variance was satisfied, the differences between individual groups of samples were tested using Student's T-test or analysis of variance. In the case when the condition of homogeneity 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 in the tested property between individual groups of samples. Post-hoc tests established statistically significant differences between individual groups of samples if they existed. If the difference is greater than 5%, it is considered significant. Presentations of comparisons between groups of samples of all investigated properties were made using box and whisker graphs.

RESULTS AND DISCUSSION

During rotary welding, fibers may break (free fibers are formed) that smooth the surface to be welded, and then the welded joint does not form. During the welding process, the tip of the dowel is intensively worn, and due to the rotation, the lignin is lost from the melt at the tip, and the tip of the dowel remains unwelded, which also reduces the strength of the joint (Fig. 3). To avoid the lack of lignin in the welding process, the idea arose to remove the cellulose fibers on the surface of the dowel using the brown-rot fungus. This increases the proportion of lignin that, together with the remaining cellulose fibers, will form a melt whose cooling forms a welded joint.

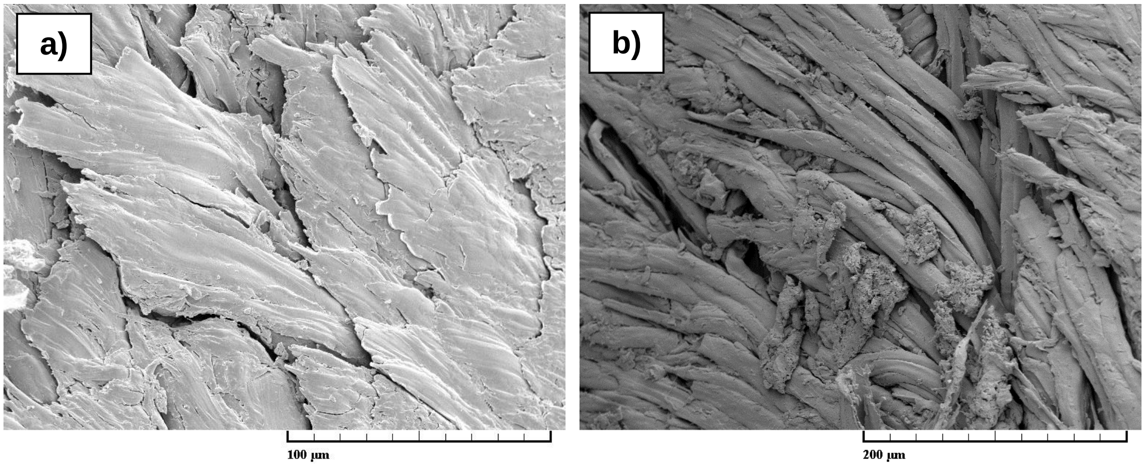

Fig. 3. Scanning electron microscopic (SEM) images of the dowel's tips:
a): intertwined fibers of the dowel oriented in the direction of rotation – welding is not achieved; and **b):** orientated fibers in the direction of rotation and small accumulations of lignin that are insufficient to form a welded joint (images used with permission from Župčić 2010)

Mass losses of dowels caused by selected brown-rot fungus (MLF) at incubation times of 2 and 4 weeks are shown in Table 2. A longer incubation time of dowels resulted in higher MLF of both grooved and smooth dowels. The surface area of a grooved dowel is larger compared to a surface area of a smooth one, so it was reasonable to expect a greater effect of the fungal mycelium on the grooved dowels compared to smooth ones (higher MLF). Considering the process of production of grooved dowels, the surface layers of wood are slightly flattened and thickened. Such a compacted and thickened wood structure represented a type of dam and had a negative effect on the development and penetration of mycelium in grooved dowels. This resulted in lower MLF of grooved dowels both after 2 and 4 weeks of incubation compared to MLF of smooth dowels (Table 2).

Table 2. Mass Losses of the Dowels Caused by Fungus (MLF) by Incubation to Mycelium of Brown Rot Fungus *Gloeophyllum trabeum*

Type of Wooden Dowels	Time of Incubation	Average MLF ± 1.96 × σ (%)
Grooved dowels	2 weeks	$1.27 \pm 2.97 \times 10^{-3}$
	4 weeks	$1.89 \pm 7.16 \times 10^{-3}$
Smooth dowels	2 weeks	$2.73 \pm 4.83 \times 10^{-3}$
	4 weeks	$6.55 \pm 43.45 \times 10^{-3}$

Hasan (2010) incubated beech wood specimens to the mycelium of the same brown-rot fungus *Gloeophyllum trabeum* in accordance with HRN EN 113-2 (2021), that is, he laid the largest surfaces of the specimens above the mycelium and obtained MLF for 3 and 6 weeks of incubation of 6.08% and 18.09%. If the results obtained in this study are compared with the data of the MLF obtained by Hasan (2010), it is evident that the dowels lost remarkably less mass compared to the specimens tested in that work. Considering the fact that the contact surface of dowels and mycelia in this research is almost 25 × smaller than the contact surface of the specimens (Hasan 2010), the mass losses obtained in this research confirm the satisfactory virulence of the selected fungus.

When welding dowels that have been biologically pretreated, there were certain difficulties and the welding process itself was more demanding than welding untreated dowels. Due to wetting of the dowels during biodegradation and re-conditioning (drying), a slight twist of few dowels occurred. Through welding such dowels, additional vibrations occurred, and it was difficult to insert the top of the dowel into the drilled hole. Additionally, brown rot reduces the mechanical properties of wood, which can cause individual dowels to break during welding, as well as the appearance of a large amount of black melt. Because of the decrease in mechanical properties and the increase in brittleness of the part of the dowels that were biologically treated, the duration of the welding process was not optimal, but it was extended because of the aforementioned reasons. This certainly had an impact on the reduction of the pull-out force of both untreated and biologically pretreated dowels. When optimizing the incubation time of dowels over fungi (biological pretreatment), it is necessary to observe the duration of the welding process, as it directly affects the pull-out force or the strength of the welded joint.

Analysis of the test results revealed that pretreatment of the dowels with the tested brown-rot fungus *Gloeophyllum trabeum* affected the pull-out force of the dowels. A statistically significant influence of the dowel incubation time on the pull-out force of the dowels was determined. The effect of biological pretreatment on the change in pull-out force was found to be significantly more pronounced on grooved dowels than on smooth dowels (Tables 3 and 4, Fig. 4). Biological degradation of smooth and grooved dowels during two weeks of incubation had a negative effect on pull-out force. At the same time, deformation of the dowels and problems during welding incurred, which ultimately resulted in a statistically significant reduction of the pull-out force compared to the pull-out force of untreated dowels (Fig. 4). Smooth dowels incubated for 2 weeks had a 13.6% reduction in pull-out force, while dowels incubated for 4 weeks achieved a 21.1% increase in pull-out force compared to untreated control dowels. Grooved dowels incubated for 2 weeks also exhibited a decrease in the pull-out force of 1.7%, and dowels incubated for 4 weeks experienced an increased pull-out force of 26.9% compared to untreated grooved dowels. Although the biological pretreatment of 4 weeks had a much greater positive influence on the pull-out force of the grooved dowels, the smooth dowels still had a higher pull-out force in all combinations (Fig. 4). One of the reasons might be because smooth dowels had an average interference fit of 2.10 mm, while grooved dowels had a 2.05 mm interference fit. The other more probable reason for the smaller pull-out force of the grooved pretreated dowels was because they had a smaller MLF.

Table 3. Breakdown Table of Descriptive Statistics (Pretreated Dowels-Pull-out Force) N=148 (No missing data in dep. var. list)

Type / Treatment of Dowel	Pull-out Force, F (N)					
	Min	Means	Max	N	Std. Dev.	Coef. of Var.
S 1	1844.95	3256.832	4599.64	24	795.329	0.244
S 2	3698.16	4565.235	5768.54	24	600.357	0.132
S C	2502.46	3769.331	5003.04	26	670.130	0.178
G 1	2026.90	3021.539	4037.51	24	624.195	0.207
G 2	3001.45	3899.372	4590.47	24	517.497	0.133
G C	2014.26	3073.724	4258.71	26	706.630	0.230
All Groups	1844.95	3592.911	5768.54	148	845.0608	0.235

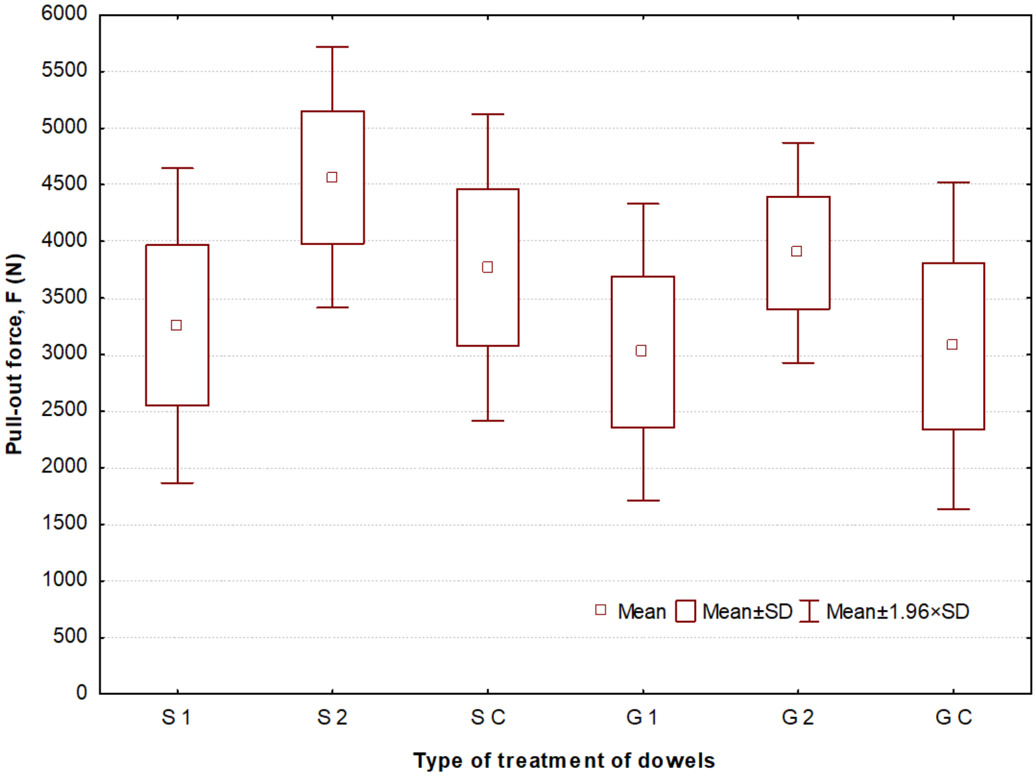

Fig. 4. The influence of dowels pretreatments onto pull-out force

Table 4. Post-hoc Scheffe Test; Variable: Pull-out Force, F (N) (Pretreated dowels-pull-out force)*

Type / treatment of dowel	{1} M=3256,8	{2} M=4565,2	{3} M=3769,3	{4} M=3021,5	{5} M=3899,4	{6} M=3073,7
S 1 {1}		0.000000	0.114367	0.900668	0.023489	0.958351
S 2 {2}	0.000000		0.002065	0.000000	0.025607	0.000000
S C {3}	0.114367	0.002065		0.009286	0.990345	0.013875
G 1 {4}	0.900668	0.000000	0.009286		0.001386	0.999928
G 2 {5}	0.023489	0.025607	0.990345	0.001386		0.002060
G C {6}	0.958351	0.000000	0.013875	0.999928	0.002060	

* Marked differences are significant at $p < 0.05000$ (red color means a significant difference between compared groups)

When the mass losses of dowels caused by the fungus (MLF) and the corresponding pull-out force (F) are compared, the results imply that the pull-out force increased nearly linearly with the increase of MLF (Fig. 5).

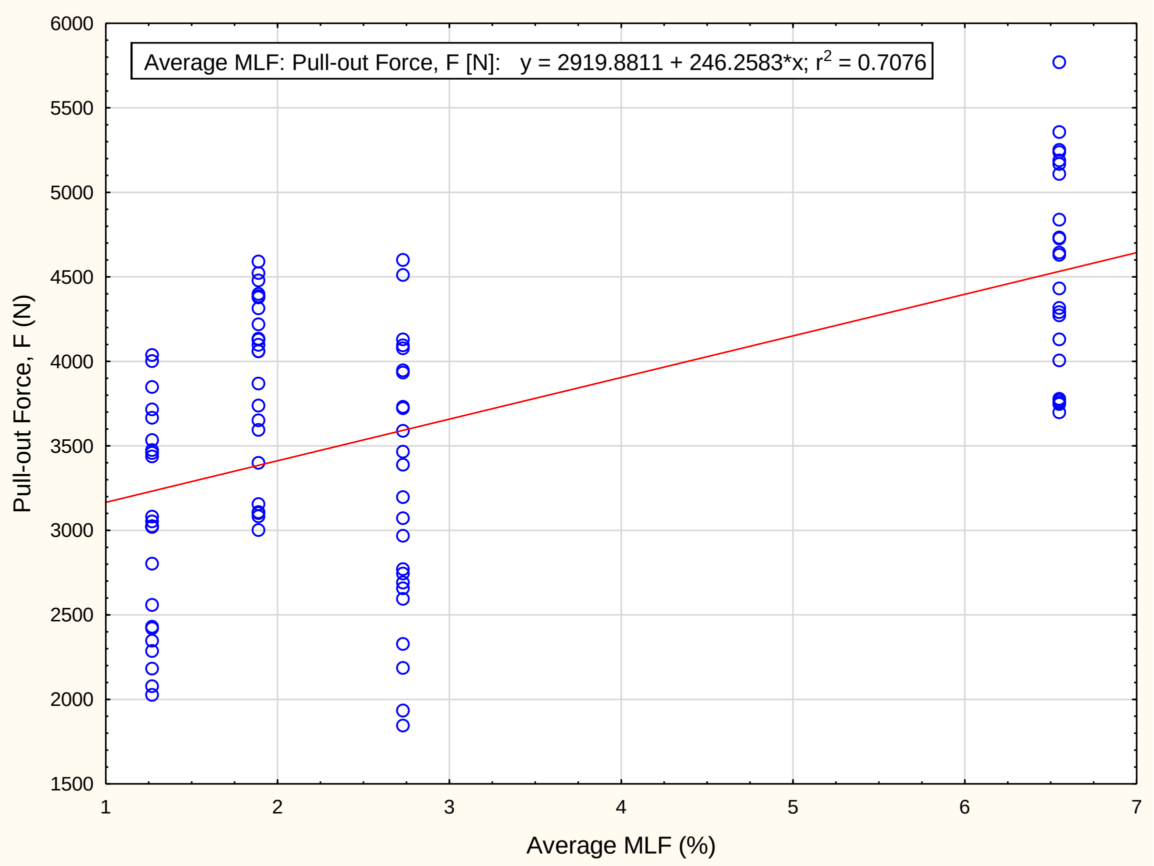

Fig. 5. The influence of MLF on Pull-out Force (F)

If the issue is viewed from the aspect of increasing the proportion of lignin in the weld melt, then this statement is logical, because a higher MLF results in a higher proportion of lignin on the surface of the dowel and, ultimately, a higher pull-out force. However, it must be kept in mind that the chosen brown-rot fungus reduces the strength of the dowel by breaking down the holocellulose part of the cell wall, so there must be an optimum MLF that will result in the highest possible pull-out force, without causing a decrease in the strength of the dowel itself. All of the above leads to the conclusion that in addition to optimizing the main welding factors (rotation frequency, dowel insertion speed, welding duration, *etc*.), it is advisable to optimize the incubation time of the dowel over the fungal mycelium. Further research into optimization of the time and process of biological pre-treatment of dowels with lignicolous fungi is suggested.

CONCLUSIONS

1. It was possible to weld smooth and grooved dowels that were biologically pretreated with lignicolous brown-rot fungus *Gloeophyllum trabeum* for 2 and 4 weeks using the optimal spin frequency.
2. Two weeks of the dowels incubation over the mycelium of the tested lignicolous fungus resulted in a reduction in pull-out force: smooth dowels by 13.6%, and grooved dowels by 1.7% compared to the control (biologically untreated) dowels.
3. Longer dowel incubation time resulted in a 26.9% increase of pull-out force with grooved dowels compared to the control ones. With smooth dowels, longer incubation resulted in a 21.1% increase in pull-out force compared to control dowels.
4. An increased number of welding errors was observed while welding biologically pre-treated dowels by applying optimal welding duration of 1 s. The optimal welding time could not be applied because of the deformed longitudinal axis due to wetting and drying of the dowels and due to the increased brittleness of the dowels. Axial deformation was more pronounced in dowels biologically pretreated for 2 weeks, while some dowels biologically pretreated for 4 weeks had increased brittleness.
5. Biological pretreatment of wooden dowels can increase the strength of welded joint, but it is necessary to optimize all factors that influence welding and the joint strength.

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REFERENCES CITED

Amirou, S., Pizzi, A., and Delmotte, L. (2020). "Investigations of mechanical properties and chemical changes occurring during welding of thermally modified ash wood," *Journal of Adhesion Science and Technology* 34(1), 13-24. DOI: 10.1080/01694234.2019.1659569

Bocquet, J. F., Pizzi, A., and Resch, L. (2007). "Full-scale industrial wood floor assembly and structures by welded-through dowels," *Holz Roh Werkst.* 65, 149-155. DOI: 10.1007/s00107-006-0170-4

Boonstra, M., Pizzi, A., Ganne-Chedeville, C., Properzi, M., Leban, J. M., and Pichelin, F. (2006). "Vibration welding of heat-treated wood," *J. Adhesion Sci. Technol.* 20(4), 359-369. DOI: 10.1163/156856106776381758

Food and Agriculture Organization of the United Nations (FAO) Regulation ISPM 15 (2019). "Regulation of wood packaging material in international trade," Food and Agriculture Organization of the United Nations, Rome, Italy.

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," *J. Adhesion Sci. Technol.* 19(13-14), 1157-1174. DOI: 10.1163/156856105774429037

Hasan, M. (2010). *Impact of Various Modification Procedures on the Biological Resistance of Wood*, Doctoral Dissertation, University of Zagreb, Faculty of Forestry, Zagreb, Croatia.

HRN EN 113-2 (2021). "Durability of wood and wood-based products – Test method against wood destroying basidiomycetes – Part 2: Assessment of inherent or enhanced durability, EN 113-2:2020," CEN – European Committee for Standardization, Brussels, Belgium.

HRN ISO 13061-1 (2015). "Physical and mechanical properties of wood – Testing methods for smaller samples of solid wood – Part 1: Determination of water content for conducting tests of physical and mechanical properties, ISO 13061-1:2014," International Organization for Standardization, Geneva, Switzerland.

HRN ISO 13061-2 (2015). "Physical and mechanical properties of wood - Testing methods for smaller solid wood samples - Part 2: Determination of density for conducting physical and mechanical properties tests, ISO 13061-2:2014," International Organization for Standardization, Geneva, Switzerland.

Jones, D., and Pizzi, A. (2007). "Frictional welding of dowels into modified wood," in: *Proceedings of the 5th COST E34, Bonding of Modified Wood*, University of Ljubljana, Bled, Slovenija, pp. 13-19.

Kanazawa, F., Pizzi, A., Properzi, M., Delmotte, L., and Pichelin, F. (2005). "Parameters influencing wood-dowel welding by high-speed rotation," *J. Adhesion Sci. Technol.* 19(12), 1025-1038. DOI: 10.1163/156856105774382444

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

Omrani, P., Mansouri, H. R., Pizzi, A., and Masson, E. (2010). "Influence of grain direction and pre-heating on linear wood welding," *Eur. J. Wood Wood Prod.* 68(1), 113-114. DOI: 10.1007/s00107-0349-6

Pizzi, A., Leban, J. M., Kanazawa, F., Properzi, M., and Pichelin, F. (2004). "Wood dowel bonding by high-speed rotation welding," *J. Adhesion Sci. Technol.* 18(11), 1263-1278. DOI: 10.1163/1568561041588192

Properzi, M., Leban, J. M., Pizzi, A., Wieland, S., Pichelin, F., and Lehmann, M. (2005). "Influence of grain direction in vibrational wood welding," *Holzforschung* 59(1), 23-27. DOI: 10.1515/HF.2005.004

Placencia, P. M. I., Rheme, M., and Pizzi, A. (2015). “Mechanical properties of welded wood joints with natural additives,” *Holztechnologie* 56(6), 5-9.

Vaziri, M., Karlsson, O., and Sandberg, D. (2019). “Wettability of welded wood. Part 1. Determination of apparent contact angle, swelling, and liquid sorption,” *Holzforschung* 75(1), 65-74. DOI: 10.1515/hf-2019-0308

Vaziri, M., and Sandberg, D. (2021). “Welding of thermally modified wood and thermal modification of the welded wood: Effects on the shear strength under climatic conditions,” *BioResources* 16(2), 3224-3234. DOI: 10.15376/biores.16.2.3224-3234

Zhang, J., Gao, Y., Zhang, J., and Zhu, X. (2018). “Influence of pretreated wood dowel with $CuCl_2$ on temperature distribution of wood dowel rotation welding,” *J. Wood Sci.* 64(1), 209-219. DOI: 10.1007/s10086-017-1693-5

Župčić, I. (2010). *Factors Influencing the Merging of Lathe Beech Elements by Welding Technique*, Doctoral Dissertation, University of Zagreb, Faculty of Forestry, Zagreb, Croatia.

Župčić, I., Mihulja, G., Govorčin, S., Bogner, A., and Grbac, I. (2009). “Welding of thermally modified hornbeam,” *Drvna industrija* 60(3), 161-166.

Župčić, I., Mijaković, M., and Grbac, I. (2011). “Influence of thermal modification of beech on the strength of longitudinally connected turned elements by rotational welding method,” *Drvna Industrija* 62(1), 9-17. DOI: 10.5552/drind.2011.1034

Župčić, I., Povrženić, K., Balaško, K., and Radmanović, K. (2022). “Temperatures in rotary welding of dowels in the beech wood,” *BioResources* 17(4), 5848-5860. DOI: 10.15376/biores.17.4.5848-5860

Yin, W., Zheng, Y., Lu, H., and Tian, Y., (2021). ”Tribological and mechanical properties of wood dowel rotation welding with different additives,” *Journal of Adhesion Science and Technology* 37(3), 411-425. DOI: 10.1080/01694243.2021.2021682

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