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Influence of Various Wood Species and Cross-Sections on Strength of a Dowel Welding Joint

Utjecaj vrste drva i presjeka na čvrstoću zavarenog moždanika

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ABSTRACT • *Rotation welding is a new method used in wood welding. Heat that develops due to the friction on contact surfaces softens and melts the wood structure (melt is produced). When the friction stops, the melt cools down and solidifies forming a firm joint.*
This research is based on the examination of the influence of various wood species and cross-sections on the strength of joints produced by rotational welding. Using rotation frequency and shifts in the orientation of the horizontal axis, a beech dowel is welded to a base made of common beach (Fagus sylvatica L.), pedunculate oak (Quercus robur L.) and Norway spruce (Picea abies L.) (hereinafter only beech, oak and spruce). Welding direction is both parallel to the orientation of the base fibres (PP) and perpendicular to the orientation of the base fibres (R, RT, T).
Research results indicate that the dowel welded to the beech base retains the largest strength, whereas the dowel welded to the spruce base reveals the weakest results. Based on the research results, it can be concluded that beech dowels welded in the direction of beech and oak bases have the best strength of a joint. In spruce samples, reaction wood was used (compression wood in conifers) with somewhat different distribution of strength depending on the welding direction.

Key words: *welding of wood, dowel joints, withdrawal strength, embedded force, wood species, anatomical orientation*

SAŽETAK • *Rotacijsko zavarivanje novija je metoda spajanja drva. Zbog trenja na kontaktnim površinama pojavljuje se toplina koja omekša i rastali strukturu drva (nastaje talina) te se formira spoj. Prestankom trenja drvo se hladi i talina otvrdnjava te nastaje čvrsti spoj.*
Istraživanje se temelji na ispitivanju utjecaja vrste drva i presjeka na čvrstoću rotacijski zavarenog spoja. Bukov moždanik je uz pomoć frekvencije vrtnje i pomaka u smjeru uzdužne osi zavaren u podlogu izrađenu od drva obične bukve (Fagus sylvatica L.), hrasta lužnjaka (Quercus robur L.) i obične smreke (Picea abies L.) (u daljnem tekstu: bukovina, hrastovina i smrekovina). Zavarivanje se obavljalo u smjeru vlakanaca podloge (PP) i okomito na njihov smjer (R, RT, T).
Rezultati istraživanja pokazali su da moždanik zavaren u bukovu podlogu ima najveću čvrstoću, dok je najslabije rezultate pokazao moždanik zavaren u smrekovu podlogu. Iz rezultata istraživanja proizlazi kako bukov moždanik zavaren u smjeru vlakanaca bukove i hrastove podloge postiže najbolje rezultate glede čvrstoće spoja. Pri za-

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varivanju moždanika u smrekovinu rabljeno je i reakcijsko drvo (kompresijsko drvo četinjača) pa je raspored čvrstoće ovisno o smjeru zavarivanja bio nešto drugačiji.

Ključne riječi: *zavarivanje masivnoga drva, spoj s moždanikom, vlačna čvrstoća, izvlačna sila, vrsta drva, tip presjeka*

1 INTRODUCTION
1. UVOD

Suthoff and Kutzer (1997) have patented and demonstrated the rotational and vibration welding of wood. Since 2000 IBOIS (Swiss Federal Institute of Technology Lausanne) has been developing and researching the method of joining wood by friction welding without adding any adhesives (Gliniorz and Natterer, 2000; Gliniorz *et al*., 2001). This welding method is successfully used for joining two or more wood elements without adding glue or other adhesives. Friction wood welding is a process that causes chemical and physical reactions; the heat, which is a result of friction, melts and softens the wood structure. After cooling, the melt turns into a very hard compound. Chemical changes start with welding and continue after the process ends (while the melt solidifies). Wood structure cools down and becomes a hard compound. In this research the focus was not on the chemical changes occurring in the wood for which the authors used the knowledge from the literature at hand. The process of rotational welding produces gas emission and results in the decomposition of evaporable polymer components in the wood (Omrani *et al*., 2008). The analysis of evaporable compounds and gases emitted, such as smoke, which appears as a by-product during the rotational welding of the dowel to the beech and spruce base, revealed that the smoke consists of water vapour and CO_2. These two are obtained by the decomposition of the components from non-crystallized lignines and some evaporable terpenes (Norway spruce). When using a zig-zag pattern of rotationally welded dowels across the interface of a butt joint between two wood planks strong joints are obtained (Omrani *et al*., 2007). The average tensile strength of commercial beech wood with a zig-zag pattern of rotationally welded dowels 10 mm in diameter (rotational movement at 1600 min^{-1}) was 0.77 ± 0.07 MPa. The results obtained also indicate that further improvement and optimization of this process should consider a minimum compression level at the end of dowel rotation.

Pizzi *et al*. (2004) investigated welding of a 10 mm diameter beech dowel to a beech base. Welding penetration was 12 mm, rotation frequency 1200 min^{-1}, and tightness 2 mm. The maximum embedded force for these parameters was 1500 N, and the average embedded force 883 N. It was observed that welding in the tangent orientation showed the best results whereas the radial orientation had the lowest values. The average embedded force for dowels of 10 mm diameter inserted to 20 mm depth in single beech block (30 x 30 x30 mm) was 1979 ± 103 N (Pizzi *et al*., 2006). The geometry of the dowel joint allowed the joint to retain up to 88 % of its initial embedded force after 24 h immersion in cold water.

Dowel welding by high-speed rotation was used to join two wood blocks and strong joints were obtained (Bocquet *et al*., 2007). Dowel angle to the surface of the wood blocks to be joined had a marked influence on the mechanical performance of the joint. When the dowel was inserted at 90° to the substrate, the dowel was subjected to and resisted a shear force only. The results obtained show that welded-dowel structural joints can satisfy both the relevant standards and outperform the equivalent nailed joints and glued-dowel joints.

Leban *et al*. (2008) investigated the impact of rotation frequency on the strength of a beech dowel welded to the base made of Norway spruce. For this a 12 mm diameter dowel was used with the frequency of 1500 min^{-1}. The average embedded force was 2145 N, and welding time 4 s.

Leban *et al*. (2004) investigated the possibility of vibration welding of beech, oak and spruce wood with 150 x 20 x 30 mm samples, welding time of 3 s, pressure after welding 2 MPa during 5 s, and constant pressure of 1.3 MPa during the welding process. The samples were welded with the frequency of 100 Hz and vibration amplitudes of 3 mm. The strength of welded joints depended on the welding line thickness and balance. A thinner welding line has the ability to produce better strength compared to a thicker welding one. The average strength of a joint for breech reached 8.72 MPa, for oak 5.43 MPa and for spruce wood 4.2 MPa. Spruce wood showed poorer welding results due to its characteristic cell implosion and crumping. This unfavourable characteristic of spruce wood influences the strength of a joint if beech and spruce wood are welded. Implosion and crumping of cell walls increases the thickness of the welding line, especially for spruce wood. Beech wood falls under the category of harder wood species and its welding line can be easily noticed because it is dark and thin, which is an indicator of a decreased implosion of the cell wall and, also of better mechanical characteristics of the joint itself.

Kanazawa *et al*. (2005) explored the influence of welding penetration (for a beech dowel welded to a beech base) in radial and tangent orientation on embedded force. In all analysed welding penetrations (10, 20 and 30 mm), tangent orientation showed the best research results.

Ganne-Chedeville *et al*. 2005 researched welding of a hard wood dowel (beech) to a hard spruce wood base without drilling any holes. Research results indicate a significant dissipation of data and very intensive scuffing of the top of the dowel.

Župčić *et al*. (2009) investigated welding of a dowel to a base made of thermally treated and untreated hornbeam base. Thermal modification was carried out at 200 °C over 48 hours. Rotation frequency for a beech dowel was 1520 min^{-1}. The research showed that thermally unmodified dowels welded to a hornbeam base (perpendicular to the fibre orientation) indicated stronger embedded force (84 % on average, which is a statistically significant difference) than dowels welded to a thermally modified base. The average embedded force for dowels welded to an untreated base was 3754 N.

The species of wood to which a dowel is welded is a very important factor. Thus, the objective of this paper was to investigate the influence of a wood species (beech, oak and spruce) on the strength, or embedded force, of a welded joint when a dowel is welded (in the same orientation or perpendicular to the fibre orientation) to a base. Apart from some of the factors mentioned above, the authors also looked into the influence of the welding orientation (radial, tangent and radial and tangent) on the strength of a joint.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

2.1 Shape and dimensions of the samples
2.1. Oblik i dimenzije uzoraka

Research in the influence of cross-sections and species of wood on the strength of a welded joint was conducted at the Faculty of Forestry of the University of Zagreb. For the purpose of this research, beech grove dowels were used and welded to beech oak and spruce bases without defect (except spruce reaction wood which was used for research). All samples were prepared by sawing, milling and shortening to the defined measure. These samples were then pierced with an 8 mm diameter spiral drill. Dimensions of the base to which a dowel was welded perpendicular to the fibre orientation were 200 x 30 x 30 (mm) with three pierces in the radial (R), tangent (T) and radial and tangent (RT) orientation depending on the factor under scrutiny (Figure 1). A 30 x 30 x 64 (mm) base with a pierce in line with the fibre orientation was used for welding a dowel in the fibre orientation. Once welded, the sample was sawn off in two identical 30 x 30 x 30 mm pieces (Figure 2). Due to elastic deformations of the wood, upon movement of the cutting edge the drill hole diameter was reduced by 0.05 mm on average. Dowels were grouped into 1000 mm sticks and had to be shortened to the correct measure. The average dowel diameter (cross-cut measures were taken on the top of the grove) was 10.04 mm. Wood material prepared in this manner (welding base and dowels) was conditioned in a laboratory (temperature 23 ± 2 °C, relative humidity 50 ± 5 %) over a six-month period. Water content was determined according to HRN ISO 3130:1999 (the Croatian standard for determining water content for testing physical and mechanical characteristics of wood). The average water content, measured after samples were dried (103 ± 2 °C), was 9.13 % for beech wood, 9.33 % for oak wood and 10.37 % for spruce wood.

After determining the water content in the wood, the same probes were used for determining wood density according to HRN ISO 3131:1999 (the Croatian standard for determining wood density for testing physical and mechanical characteristics of wood). The average density for beech wood was 0.68 g/cm³, 0.69 g/cm³ for oak wood and 0.45 g/cm³ for spruce wood.

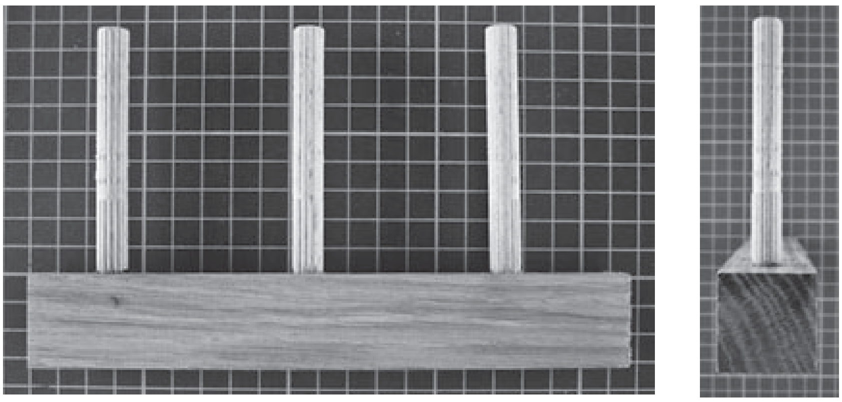

Figure 1 Test sample: Oak dowels welded perpendicular to the fibre orientation (RT)
Slika 1. Ispitni uzorak hrastovine, moždanici zavareni okomito na smjer vlakanaca (RT)

a) b) c)

Figure 2 Cross-section of the dowel welded parallel to the fibre orientation for: a) spruce; b) oak; c) beech
Slika 2. Presjek zavarenog moždanika u smjeru vlakanaca: a) u smrekovinu; b) u hrastovinu; c) u bukovinu

Table 1 Samples used in the research
Tablica 1. Uzorci rabljeni u istraživanju

Code *Oznaka*	**Description** / *Opis*
BPP	dowel welded to beech wood in the fibre orientation (transverse cross-section) *moždanik zavaren u bukovinu u smjeru vlakanaca (poprečni presjek)*
HPP	dowel welded to oak wood in the fibre orientation (transverse cross-section) moždanik zavaren u hrastovinu u smjeru vlakanaca (poprečni presjek)
SPP	dowel welded to spruce wood in the fibre orientation (transverse cross-section) *moždanik zavaren u smrekovinu u smjeru vlakanaca (poprečni presjek)*
BR	dowel welded to beech wood perpendicular to the fibre orientation (radial orientation) *moždanik zavaren u bukovinu okomito na vlakanca (radijalni smjer)*
HR	dowel welded to oak wood perpendicular to the fibre orientation (radial orientation) *moždanik zavaren u hrastovinu okomito na vlakanca (radijalni smjer)*
SR	dowel welded to spruce wood perpendicular to the fibre orientation (radial orientation) *moždanik zavaren u smrekovinu okomito na vlakanca (radijalni smjer)*
BRT	dowel welded to beech wood perpendicular to the fibre orientation (radial and tangent orientation) *moždanik zavaren u bukovinu okomito na vlakanca (radijalno-tangentni smjer)*
HRT	dowel welded to oak wood perpendicular to the fibre orientation (radial and tangent orientation) *moždanik zavaren u hrastovinu okomito na vlakanca (radijalno-tangentni smjer)*
SRT	dowel welded to spruce wood perpendicular to the fibre orientation (radial and tangent orientation) *moždanik zavaren u smrekovinu okomito na vlakanca (radijalno-tangentni smjer)*
BT	dowel welded to beech wood perpendicular to the fibre orientation (tangent orientation) *moždanik zavaren u bukovinu okomito na vlakanca (tangentni smjer)*
HT	dowel welded to oak wood perpendicular to the fibre orientation (tangent orientation) *moždanik zavaren u hrastovinu okomito na vlakanca (tangentni smjer)*
ST	dowel welded to spruce wood perpendicular to the fibre orientation (tangent orientation) *moždanik zavaren u smrekovinu okomito na vlakanca (tangentni smjer)*
PP	transversal cross-section / *poprečni presjek*
T	tangent cross-section / *tangentni presjek*
R	radial cross-section / *radijalni presjek*
RT	radial - tangent cross-section / *radijalno-tangentni presjek*

In total 365 samples were welded, and 359 samples were then used for further research. The code of samples used in the research is described in Table 1. Six samples started cracking during the welding process and were dismissed from further analysis. Welding penetration was 20 mm with constant rotation frequency of 1520 min^{-1}. The same pressure to the joint elements was kept after rotation for three seconds on average (min. two, max. four seconds). The average welding tightness was 2.09 mm.

2.2 Test of embedded force
2.2. Ispitivanje izvlačne sile

Tests on beech dowels rotationally welded to the base made of beech, oak and spruce wood were performed on the universal mechanical testing machine at the Faculty of Forestry of the University of Zagreb with testing time interval of 5 mm/min. A computer was used for measuring the force and displacement, and all values were accurately determined to the accuracy of 5 N. This research used 359 samples in total, which were welded precisely without any cracks caused by the welding process or any other errors.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

The research results presented in Table 2 and Figure 3 indicate that the species of wood and orientation of dowel welding (parallel and vertical to the fibre orientation) have a considerable effect on embedded force, that is the strength of a joint (with identical welding parameters used for all samples and under assumption that the joint surface is also identical). The best results for the embedded force were found in beech samples with a dowel welded to transverse cross-section, or in the wood fibre orientation (5144.8 N on average), which was expected. There is a significant statistical difference (Table 3) between dowels welded parallel and perpendicular to the fibre orientation. In dowels welded perpendicular to the fibre orientation (R, T, RT), values for embedded force did not indicate any significant statistical difference (Table 3). Župčić (2010) conducted tests in order to investigate the influence of the welding orientation on dowels welded to a beech base and obtained very similar distribution of embedded force values. When welding grove dowels in the conditions described above, welded dowel surface is 560 mm^2, which is 16 % less compared to the surface before welding (Župčić, 2010). The average strength of welded joints in beech was 8.7 N/mm^2 and of glued joints 8.0 N/mm^2.

Distribution of embedded force values measured on oak and beech samples indicated very similar results; the only difference is that the values were lower with a significant statistical difference. The average embedded force value measured on dowels welded to the oak base parallel to the fibre orientation (PP) was

Table 2 Descriptive statistics for embedded force depending on wood species and cross-section
Tablica 2. Deskriptivna statistika izvlačne sile u ovisnosti o vrsti drva i presjeku

Code *Oznaka uzorka*	Number of samples *Broj uzoraka*	Embedded force						
		Means *Aritmetička sredina izvlačne sile* N	Std. Dev. *Standardna devijacija izvlačne sile* N	Minimum *Minim. izvlačna sila* N	Maximum *Maks. izvlačna sila* N	Q25 *Izvlačna sila Q25* N	Median *Izvlačna sila medijan* N	Q75 *Izvlačna sila Q75* N
BPP	31	5144.8	518.1	4190	6280	4660	5300	5420
HPP	30	4477.3	389.9	3560	5190	4240	4520	4750
SPP	32	1410.6	298.6	900	2220	1220	1355	1595
BR	30	4778.3	309.8	4300	5330	4520	4760	5050
HR	28	4166.8	370.6	3420	4850	3925	4180	4440
SR	28	2674.3	508.5	1900	3650	2250	2645	3105
BRT	30	4754.0	460.9	3150	5750	4610	4710	5040
HRT	30	3961.3	428.7	3020	4990	3660	3995	4190
SRT	30	1924.3	185.0	1540	2240	1780	1945	2040
BT	30	4846.7	338.4	4040	5540	4680	4810	5060
HT	30	4000.3	385.0	3280	4610	3640	4020	4220
ST	30	2688.3	824.1	1350	4200	2060	2370	3700
All groups *Sve grupe*	359	3730.1	1285.9	900	6280	2400	4130	4700

4477.3 N, or 13 % less than the values for beech samples. There is a significant statistical difference between dowels welded parallel and perpendicular to the fibre orientation. In dowels welded perpendicular to the fibre orientation (R, T, RT), embedded force values did not reveal any significant statistical difference.

Spruce samples indicated significantly different value distribution since reaction wood had been used for the preparation of samples. The largest average value of embedded force in ST and SR spruce samples was recorded in samples with reaction wood, and the smallest in SPP samples without reaction wood. It can be concluded that the reaction wood increases the embedded force of the above mentioned samples in comparison with SPP samples. It is a well-known fact that reaction spruce wood has much wider growth rings with a larger share of late wood resulting in higher density. Reaction spruce wood also has a larger portion of higher lignine content and lower cellulose content. The research results (Župčić, 2010) indicate that differences in density for the same wood species influence the strength of a welded joint where an increased density results in an increased strength of a welded joint. Chemical, physical and mechanical changes also influence the strength of a welded joint. However, this is not the focus of this research.

The average embedded force value for dowels welded to the spruce base parallel to the fibre orientation (PP) was 1410.6 N or 73 % less than the value for beech samples or 68 % less than the value for oak wood. Spruce wood indicated lower welding results due to its characteristic implosion and crumpling of cell walls (Lebanet *al*., 2004). During welding time a dowel volume decreased whereas the hole volume increased with two side-effects: cell walls implode, and interface surface density increases from its regular values which are up to 1.4 g/cm^3 (Pizzi *et al*., 2004). The other part of the volume vanishes due to frictional abrasion (of the dowel and side walls inside the hole) and draining of the melt from the interface zone. When the beech dowels was welded to the beech base parallel to the fibre orientation, the zone of implosion of cell walls exceeded 1.5 mm (Župčić, 2010).

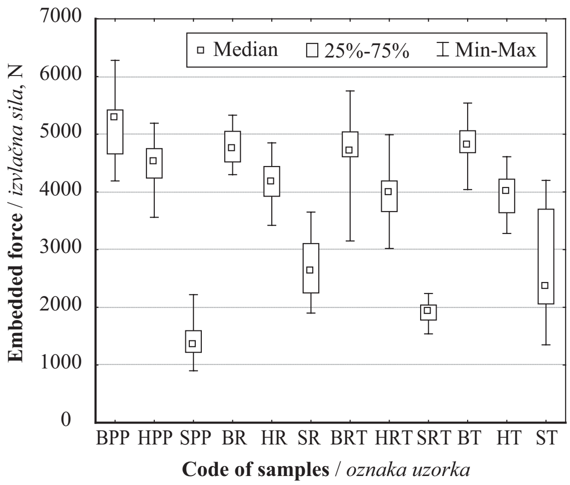

Figure 3 Influence of wood species and cross-section on embedded force
Slika 3. Utjecaj vrste i presjeka drva na izvlačnu silu

The research was also focused on the influence of ring thickness in SR and ST samples. The research results (Figure 4) indicate that the embedded force decreases with the increase of the number of growth rings, i.e. the decrease of growth ring width and share of late wood. It should be assumed that the width of growth rings in reaction spruce wood influences the strength of a welded joint. For the purpose of further researching this area, it is necessary to provide more samples and to research in detail the influence of reaction wood on the strength of joints. Dependency of embedded force and

Table 3 Multiple comparison rankings (Kruskal-Wallis test: $H(11, N = 359) = 297.9809$ $p = 0.000$)
Tablica 3. Višestruka usporedba rangova (Kruskal-Wallis test: $H(11, N = 359) = 297{,}9809$ $p = 0{,}000$)

Code *Oznaka uzorka*	BPP R:308.4	HPP R:233.7	SPP R:20.4	BR R:274.8	HR R:189.5	SR R:92.6	BRT R:271.7	HRT R:167.9	SRT R:50.9	BT R:285.3	HT R:171.1	ST R:94.4
BPP		0.3263	0.0000	1.0000	0.0007	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0000
HPP	0.3263		0.0000	1.0000	1.0000	0.0000	1.0000	0.9330	0.0000	1.0000	1.0000	0.0000
SPP	0.0000	0.0000		0.0000	0.0000	0.4742	0.0000	0.0000	1.0000	0.0000	0.0000	0.3306
BR	1.0000	1.0000	0.0000		0.1161	0.0000	1.0000	0.0044	0.0000	1.0000	0.0072	0.0000
HR	0.0007	1.0000	0.0000	0.1161		0.0316	0.1686	1.0000	0.0000	0.0291	1.0000	0.0324
SR	0.0000	0.0000	0.4742	0.0000	0.0316		0.0000	0.3789	1.0000	0.0000	0.2638	1.0000
BRT	1.0000	1.0000	0.0000	1.0000	0.1686	0.0000		0.0070	0.0000	1.0000	0.0114	0.0000
HRT	0.0000	0.9330	0.0000	0.0044	1.0000	0.3789	0.0070		0.0008	0.0007	1.0000	0.4018
SRT	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.0000	0.0008		0.0000	0.0004	1.0000
BT	1.0000	1.0000	0.0000	1.0000	0.0291	0.0000	1.0000	0.0007	0.0000		0.0013	0.0000
HT	0.0000	1.0000	0.0000	0.0072	1.0000	0.2638	0.0114	1.0000	0.0004	0.0013		0.2785
ST	0.0000	0.0000	0.3306	0.0000	0.0324	1.0000	0.0000	0.4018	1.0000	0.0000	0.2785	

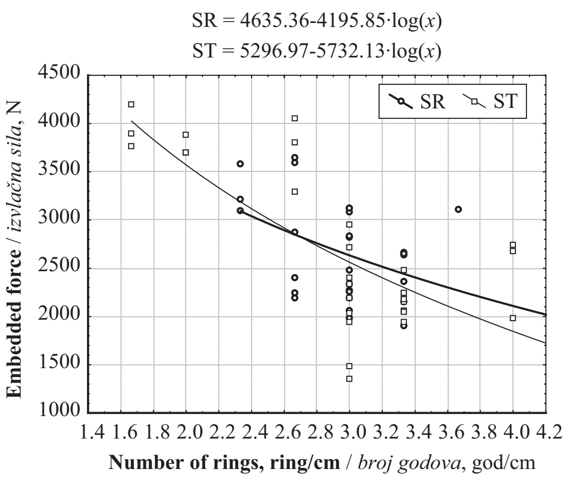

Figure 4 Influence of the number of growth rings (SR and ST) to embedded force
Slika 4. Utjecaj broja godova (SR i ST) na izvlačnu silu

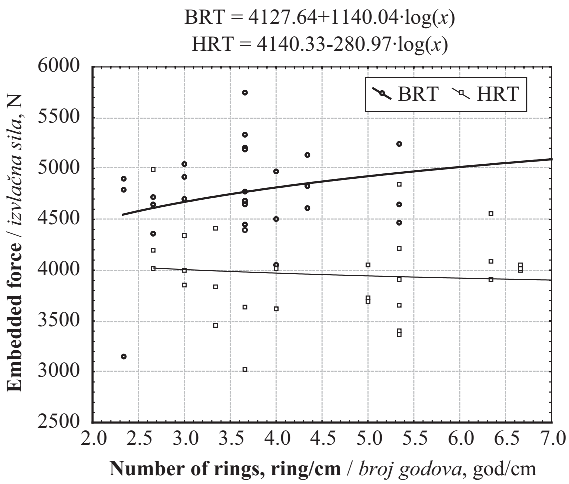

Figure 5 Influence of the number of growth rings (BRT and HRT) on embedded force
Slika 5. Utjecaj broja godova (BRT i HRT) na izvlačnu silu

number of growth rings of SR samples may be described by the following equation: $y = 4635.36 - 4195.84 \cdot \log x$, while ST samples may be described by the equation where $y = 5296.97 - 5732.13 \cdot \log x$.

Figure 5 indicates a slow growth for beech wood and a mild drop for oak wood in respect of embedded force with decreased width of growth rings (where the number of growth rings per centimetre increased). The influence of growth ring width has not been unequivocally determined, as indicated in the research papers (Župčić, 2010). Growth ring width has an effect on the strength of a joint but it is not statistically relevant. Beech and oak wood are species of wood with important differences in anatomic, physical, mechanical and chemical characteristics depending on the biotope, soil, altitude and position in the tree. These factors influenced the dissipation of data because the samples had been selected from the regular production of edge glued panels. Dependency of embedded force and number of growth rings for BRT samples may be described by the following equation: $y = 4127.64 + 1140.08 \cdot \log x$, while HRT samples may be described by the equation where $y = 4140.33 - 280.97 \cdot \log x$.

4 CONCLUSION
4. ZAKLJUČAK

Rotational welding can be successfully used for welding beech grove dowels to bases made of beech, oak and spruce wood parallel and perpendicular to the fibre orientation. The research results lead to the conclusion that the influence of wood species and welding orientation on the strength of a welded joint is statically relevant.

The research results reveal that beech wood is the best wood species for welding dowels, regardless of the fibre orientation - parallel or vertical. Statistically significant differences (Table 3) appear for all combinations except for oak wood welded to a transverse cross-section or perpendicular to the fibres in the radial orientation.

The average values for the embedded force measured in dowels welded to spruce wood are statistically significantly lower in relation to the average values for the embedded force measured in dowels welded to beech and oak wood. Such results were expected because of spruce wood structure, composition and other characteristics. Reaction wood also has a significant influence since it improves the strength of a welded joint.

Dowels welded parallel to the fibre orientation indicated higher values for the embedded force than dowels welded perpendicular to the fibre orientation (beech and oak wood test samples). Tests on spruce wood indicated that dowels welded perpendicular to the fibre orientation have stronger embedded force than dowels welded parallel to the fibre orientation due to the reaction wood which is known for its higher density and higher proportion of late wood.

Width of a growth ring does not have much statistical significance except for spruce wood (reaction wood) for which the embedded force grows with the increase of growth ring width.

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