

Influence of Air Humidity Variation on Strength of Rotary Welded Dowel Joints of Pinewood

Utjecaj promjene vlažnosti zraka na čvrstoću kružno zavarenih spojnih elemenata od borovine

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ABSTRACT • A rotary welded joint is a combination of wood in which chemical and physical reactions occur due to friction. During the welding process, heat is generated which softens and melts the wood structure. In this way, interlocked wood fibres in the lignin melt are created within the joint. As the welded joint cools down, it becomes a tight weld. The paper describes the research based on studying the impact of individual factors on the welded joint. Outcome variables are the average ring width, the water content in the wood, and the influence of different humidity levels on the strength of rotary welds. Samples were subjected to the influence of different humidity levels achieved by air conditioning, magnesium chloride and sodium chloride. Absolutely dry samples exhibited the lowest embedded force values (the average embedded force value for heartwood amounted to 1901 N and for sapwood 1920.36 N), while the air conditioned samples (the average embedded force value amounted to 2649.06 N; for sapwood 2679.6 N and for heartwood 2619.6 N). The samples exposed to sodium chloride (the average embedded force value amounted to 2907.7 N; for sapwood 2766.07 N and for heartwood 3049.33 N) exhibited the highest embedded force values. This paper presents a descriptive statistical analysis of the strength of rotary welded dowels in the pine base. The aim of the study was to research the influence of different air humidity levels on the embedded force of Scots pine rotary welds. As the air relative humidity and temperature change during the daily application of the product (which affects the moisture content in the wood), the knowledge on the influence that humidity and water content in the wood exert on the welded joint strength turns out to be of great importance for its use.

Keywords: welding solid wood, Scots pine (*Pinus sylvestris* L.), dowels, strength of welded joints, weld factors, embedded force, the impact of humidity on wood, wood moisture content

SAŽETAK • Kružno zavareni spoj jest spoj drva u kojemu se zbivaju kemijsko-fizikalne reakcije pod utjecajem trenja. Tijekom procesa zavarivanja stvara se toplina, zbog koje struktura drva omekša i rastali se, pa se te drvena vlakanca u talini lignina međusobno isprepletu. Pri hlađenju zavarenog spoja nastaje čvrsto zavareni spoj. U radu je opisano istraživanje utjecaja pojedinih čimbenika na zavareni spoj, u sklopu kojega su promatrani sadržaj vode u drvu te utjecaj različite vlažnosti zraka na čvrstoću kružno zavarenih spojeva. Uzorci su izlagani zraku različite vlažnosti, što je postignuto njihovim kondicioniranjem te solima magnezijeva i natrijeva klorida. Apsolutno suhi

¹ Authors are researcher, professor and associate professor at University of Zagreb, Faculty of Forestry, Zagreb, Croatia.

¹ Autori su istraživač, profesor i izvanredni profesor Sveučilišta u Zagrebu, Šumarski fakultet, Zagreb, Hrvatska.

uzorci pokazali su najniže vrijednosti izvlačne sile (prosječna vrijednost te sile za srž iznosila je 1901 N, a za bjeljiku 1920,36 N), a zatim slijede klimatizirani uzorci (prosječna vrijednost izvlačne sile iznosila je 2649,06 N; za bjeljiku 2679,6 N, a za srž 2619,6 N). Uzorci izloženi natrijevu kloridu pokazali su najviše vrijednosti izvlačne sile (njezina prosječna vrijednost iznosila je 2907,7 N; za bjeljiku 2766,07 N, a za srž 3049,33 N). U radu je prikazana deskriptivna statistička analiza čvrstoće moždanika kružno zavarenih u borovinu. S obzirom na to da se pri svakodnevnoj uporabi proizvoda mijenja relativna vlažnost zraka i temperatura (što utječe na promjene sadržaja vode u drvu), poznavanje utjecaja vlažnosti zraka i sadržaja vode u drvu na čvrstoću zavarenog spoja vrlo je važno za njegovu primjenu.

Ključne riječi: zavarivanje masivnog drva, borovina (*Pinus sylvestris L.*), moždanik, čvrstoća zavarenog spoja, čimbenici zavarivanja, izvlačna sila, utjecaj vlažnoga zraka na drvo, sadržaj vode u drvu

1 INTRODUCTION

1. UVOD

Humankind is showing an increasing environmental awareness and social responsibility nowadays so that the demand for environmentally friendly products is increasing as well. The application of welded wood joints may play a major role in the production and use of wood products. Welded joints not only achieve approximately the same embedded force values as glued joints, but they are also ecologically friendly as only natural materials are used for welding. During their recycling or incineration, such joints do not release toxins and they behave as natural wood. (Stamm *et al.*, 2005).

Wood welding is done by heat and pressure (rotation and vibration) generated between one or more elements. The advantage of this procedure is that no adhesive is needed and, as such, it is the most environmentally benign. During the welding process, the components (lignin and hemicelluloses) soften thermally, which leads to polymerization, while surface wood layers melt when in contact (due to friction between materials). As a result, the cell wall in the interfacial zone is destroyed and the density in the welding zone increases considerably. Mechanical friction (which produces high temperatures), pressure forces and chemical reactions at the cooling stage make cell walls burst. The joints produced in this way can be compared to other ways of bonding. Chemical changes resulting from welding have not been included in this research. Instead, already known facts from available literature have been used. Much recent research has been dedicated to wood to find new ways of application of this valuable and renewable raw material (Župčić, 2010).

During the rotation in wood welding, the dowel surface and volume decrease, while the welding hole increases. The wood density in the welding zone increases considerably because of the total destruction of cells. Wood welding is determined by the temperature, melting of certain amorphous polymeric substances and by mutual bonding of wood tissue in the wood structure. Certain studies showed that the welded joint could be much stronger than the glued joint (Župčić, 2010).

This paper presents the descriptive statistical analysis of the strength of a rotary welded dowel that was exposed to different humidity levels. The aim was to research the influence of different humidity levels on the strength of welded joints with regard to the fact that

relative humidity and temperature change during the application of the product, which affects the water content in the wood. The knowledge of the influence that relative air humidity has on the welded joint strength turns out to be important for the future application in manufacture and for everyday use.

The research is based on studying the impact of individual factors on the welded joint. The factors that were observed include the water content in the wood and impact of different humidity levels on the strength of rotary welded joints. Eighty samples were used for the research. Three holes were drilled on each sample into which dowels were welded. After the selection of 80 samples, they were divided into two groups consisting of 40 samples from the sapwood zone, and 40 samples from the heartwood zone. The samples divided in this way were exposed to different air humidity levels. One group consisted of samples that were absolutely dry, the other group of air-conditioned samples and the remaining two of samples exposed to different of air humidity (obtained by magnesium chloride and sodium chloride).

Pizzi *et al.* (2006) researched the influence of water on the welded joint. A grooved beech dowel having 10 mm in diameter was welded to a beech base (30 mm × 30 mm × 30 mm) in an 8 mm hole. The welding depth was 20 mm, the rotation frequency 1515 revolution/min, and the weld time was 3 s. The control samples were glued using PVAc adhesive and conditioned over 24 h. The samples were immersed in cold water over a period of 24 hours. The research results show that the embedded force of the treated samples amounted to 88 % of the embedded force of the untreated samples.

Jones and Pizzi (2007) studied the influence of cold and boiling water on the strength of the welded joint of modified Sitka spruce wood. The results show a greater embedded force of the joints of thermally and chemically (alcohol based) modified wood during a 2-hour period of exposure to boiling water. The unmodified samples exhibited the greatest embedded force under normal conditions, whereas the chemically modified samples (modified by an acetylation agent) exhibited the greatest embedded force when exposed to cold water. It was demonstrated that the technique of modified wood welding is applicable, and that it improves the joint strength when exposing the welded joints to the influence of humidity and moisture. The research results show that the use of modified wood for welding can produce a joint that is more resistant to humidity. This opens up new opportunities for the application of the wood welding technique.

Leban *et al.* (2008) studied the impact of frequency on rotational welding. They used grooved beech dowels (*Fagus Sylvatica*) of 12 mm in diameter and 80 mm in length. The samples were made of spruce wood (*Picea Abies*) with a water content of 12 %. Receiver holes had a diameter of 9.5 mm to a depth of 15 mm, and of 8 mm to a depth of 46 mm. Embedded strength was examined on the samples that were welded at the frequencies of 1500, 4000, 6000 and 6500 min⁻¹. Welding time was between 2 and 4 s. The best results in embedded strength were obtained at a frequency of 1500 min⁻¹, whereas an increase in frequency resulted in lower strength. Higher welding frequencies produced a higher concentration of destroyed tissue i.e. a high increase in temperature was generated, so that melted material shifted further away from the bond line and thus created a gap.

Župčić *et al.* (2014) examined the impact of wood species such as beech, oak and spruce on the welded joint strength by examining the embedded strength (parallel and perpendicular to the fibres) and the impact of the ring width on the joint strength. Altogether 365 samples were made, out of which 359 were used for further research (bursting occurred in six samples). There were 16 different sample types with the dimensions of 200 mm × 30 mm × 30 mm with 30 sample pieces of each type. For each sample, grooved dowels were welded into drilled holes of 8 mm in diameter in the radial, radial-tangential and tangential direction. The sample type, where the hole was drilled in the same direction as the fibre orientation, had the dimensions of 30 mm × 30 mm × 64 mm, and when the sample was cut to be examined under the magnifying glass, its dimensions were of 30 mm × 30 mm × 30 mm. The average dowel was 10.04 mm in diameter and the weld penetration amounted to 20 mm. The rotation frequency was 1520 min⁻¹ and the average tightness after the welding was 2.09 mm. A computer for measuring force and displacement was used for testing the embedded strength on the universal testing machine so that values were determined with a 5 N certainty. The testing was carried out with a 5 mm/min displacement. The results showed that there is a significant difference between the dowels welded parallel and perpendicular to the fibre orientation. The beech samples, with the dowels welded in the same direction as the fibre orientation, showed the best embedded strength values. The spruce samples, with the dowels welded in the same direction as the fibre orientation, showed the lowest embedded force values. In case of the dowels welded perpendicular in the radial, radial-tangential and tangential direction no statistically significant difference was recorded.

2 MATERIALS AND METHODS

2. MATERIJALI I METODE

2.1 Solid wood selection

2.1. Izbor masivnog drva

Scots pine (*Pinus sylvestris* L.) was used for the research. The material was selected randomly from the stack of sawn dry timber. The only selection criterion

was that the sawn timber be of regular structure, without any knots, cracks and damages. Scots pine belongs to conifers. Conifer tissue between wood rays consists exclusively or mostly of tracheids arranged in regular radial sequences. Such wood structure is suitable for evenly distributed stress along the joint and, therefore, for the preparation and processing of welding samples of good quality. Materials required for the testing were taken from the commercial stack so that possible changes during the testing could be linked to wood elements from the standard manufacture. Results obtained in this way could reveal joint properties that could be applied later under real conditions.

2.2 Preparation of samples for welding perpendicular to fibre orientation

2.2. Priprema uzoraka za zavarivanje okomito na smjer vlakana

2.2.1 Determination of initial moisture content in samples

2.2.1. Određivanje početnog sadržaja vode u uzorcima

The initial moisture content was determined by the gravimetric method according to HRN ISO 13061-1:2015 by Eq. 1:

$$W = \frac{m_w - m_2}{m_2} \cdot 100 \quad (1)$$

where W is the moisture content in the wood after 7 days according to HRN ISO 13061-1:2015 (%), m_w is the initial probe mass (g) and m_2 is the probe mass after 7 days (g).

Wood density was determined on the same samples according to HRN ISO 13061-2:2015 by Eq. 2:

$$\rho = \frac{m}{V} \quad (2)$$

where ρ is wood density (g/cm³), m = mass (g) and V = volume (cm³).

2.2.2 Preparation of Scots pine specimens

2.2.2. Priprema uzoraka borovine

At the beginning of the samples preparation, specimens were taken to determine the initial moisture content and wood density (pinewood). Specimens were divided into two sample groups, 12 heartwood specimens and 12 sapwood specimens, which were used to determine the initial moisture content. Specimen dimensions and masses were measured to determine the specimen moisture content and density by the gravimetric method. The average moisture content in sapwood specimens amounted to 10.25 % (the minimum moisture content was 9.71 and maximum 12.37 %), while the average density amounted to 0.498 g/cm³ (the minimum density was 0.488 g/cm³ and maximum 0.511 g/cm³). The average moisture content in heartwood samples amounted to 9.78 % (the minimum moisture content was 9.21 % and maximum 11.99 %), while the average density amounted to 0.560 g/cm³ (the minimum density was 0.549 g/cm³ and maximum 0.569 g/cm³).

During their preparation all specimens were sawn, planed and cut down to their final dimensions, and receiver holes were drilled. Specimens with dimensions of 30 mm × 200 mm × 30 mm were used for the research. Sawn and planed laths with the dimen-

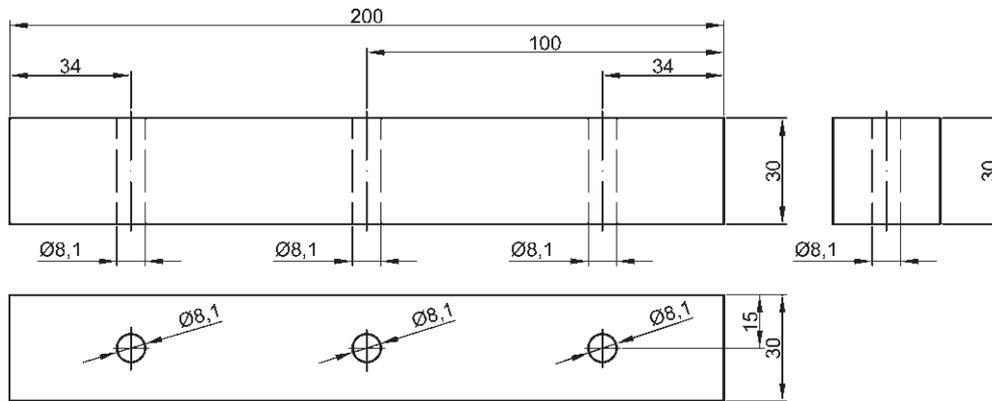


Figure 1 Testing sample for dowel welding
Slika 1. Ispitni uzorak pripremljen za zavarivanje moždanika



Figure 2 Specimens prepared for drying
Slika 2. Uzorci pripremljeni za sušenje

sions of cross section of 30 mm × 30 mm were cut to the length of 200 mm by transversal sawing. After transversal sawing of the sample laths, specimens were divided into 40 specimens from the sapwood zone and 40 specimens from the heartwood zone. All specimens were of radial-tangential texture.

Three receiver holes were drilled in each specimen. The distance between the hole ends was 34 mm, while the middle hole was made 100 mm from the sample end. The holes had a diameter of 8.1 mm and the welding direction was radial-tangential. Figure 1 shows the sample with drilled holes of 8.1 mm.

The sample holes were drilled by means of a tightly fixed drilling machine on the working desk at the rotation frequency of 1520 min⁻¹ with the spiral steel drilling bit of 8.1 mm in diameter and HSS mark. The prepared samples were weighed on a digital weighing scale with the reading possibility of 0.0001 g

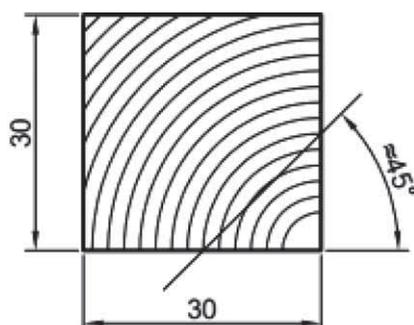


Figure 3 Manner of determining the ring width
Slika 3. Način određivanja širine goda

and then dried in an oven at the temperature of (103±2) °C and 0 % moisture content (Figure 2).

Besides the density and the average water content, the average ring width was determined as well by counting rings along the 30 mm width. The average ring width was measured by dividing the width of 30 mm (radial direction) by the number of rings on that width (Figure 3). The average ring width on heartwood samples amounted to 1.74 mm and on sapwood samples to 1.98 mm.

2.2.3 Dowel preparation

2.2.3. Priprema moždanika

Dowels were needed for the testing. They were obtained from smooth wooden sticks of 1000 mm in length and 10 mm in diameter and they were sawn to the length of 120 mm. Subsequently, their ends were bevelled by 1 mm at the angle of 45°.

Dowel bevelling was necessary for easier welding of the samples. After the processing, the dowels were weighed on the digital weighing scale with the reading possibility of 0.0001 g and put in the oven together with the samples at the temperature of (103 ± 2) °C. The average moisture content and density were obtained by the gravimetric method. The average moisture content of the dowels amounted to 9.57 % according to HRN ISO 13061-1:2015 and the dowel density to 0.662 g/cm³ according to HRN ISO 13061-2:2015.

2.3 Dowel rotary welding in prepared specimens

2.3. Kružno zavarivanje moždanika u pripremljene uzorke

After drying in the oven at (103±2) °C, the specimens and dowels were weighed on a digital scale. The weighed specimens and dowels were put into plastic boxes to keep their moisture content constant during their transport to the room for dowel welding. The dowel rotary welding in specimens was performed in a room with the temperature of 22 °C and the relative humidity of 58 %.

The sample welding was carried out by an adapted device with the possibility of dowel rotation. The welding was performed by rotating the dowel at the rotation frequency of 1520 min⁻¹ during the welding. The time needed to weld the dowel into the specimen



Figure 4 Testing specimens prepared for testing
Slika 4. Uzorci pripremljeni za ispitivanje

was 1.4 s, while the pressure on the dowel after the welding was applied for 3 to 5 seconds. The weld penetration amounted to 20 mm. The specimen, into which the dowels were welded, was immovable (static). Figure 4 shows the testing specimen prepared for embedded force testing.

After 80 samples had been welded, the probes were divided into four groups. Within each group there were 10 samples of sapwood and 10 samples of heartwood (three holes were drilled on each sample, each group with 60 welded dowels, 30 on heartwood samples and 30 on sapwood samples). One of the four sample groups (10 samples of sapwood and 10 samples of heartwood) was tested on the universal testing machine immediately.

The other sample group was conditioned under the laboratory conditions for a month at the temperature of (23 ± 2) °C and the relative humidity of (50 ± 5) %. After exposing the samples to climatic conditions for a month, the samples were transferred to the room equipped with the universal testing machine at the Department for Wood Science. Immediately after the testing, the water content was measured by the gravimetric method. The average water content after the exposure to climatic conditions amounted to 10.05 %.

The third sample group was exposed to magnesium chloride ($MgCl_2$) and the fourth to sodium chlo-

ride ($NaCl$). The magnesium and sodium chloride salts were dissolved in water until the mixture turned into mesh. After the mixture has been prepared, metal stands were put in plastic boxes in which samples were placed. The boxes with closed samples were left for four weeks (25 days). After removing the samples from the boxes, the water content was determined.

The average water content for the samples exposed to sodium chloride ($NaCl$) amounted to 13.05 % (the average water content for heartwood samples was 12.41 % and for sapwood samples 13.70 %). The average water content for the samples exposed to magnesium chloride ($MgCl_2$) amounted to 8.87 % (the average water content for heartwood samples was 8.71 % and for sapwood samples 9.03 %).

2.4 Embedded force testing

2.4. Ispitivanje izvlačne sile

The testing was carried out on the universal testing machine. Due to the specific nature of the testing, a new part for the universal testing machine was made for catching dowels to avoid their slipping out so that the testing could be carried out smoothly (Figure 5). The universal testing machine adapted in this way allows the centreline axis of the sample to be parallel with the centreline axis of the universal testing machine on which the force acts. The displacement on the universal testing machine during the testing was 5 mm/min.

3 RESULTS AND DISCUSSION

3. REZULTATI I RASPRAVA

Properties of the welded joint were determined by measuring the embedded force of the dowel from the sample. All research results were processed in *Microsoft Excel 13* and *Statistica 12* programs and the embedded force results were compared accordingly after the testing (Table 1). Figure 6 shows the comparison of embedded forces for all sample groups. It may be concluded that there is no significant statistical difference ($p < 0.001$) between embedded force values of the conditioned samples (heartwood and sapwood), the

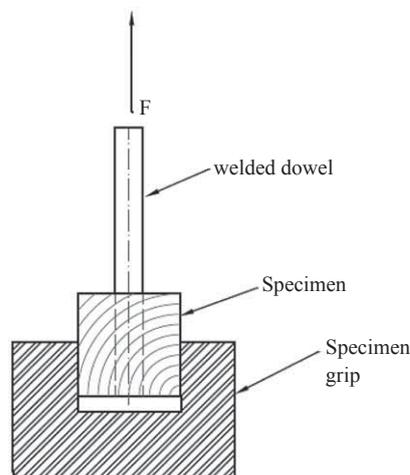
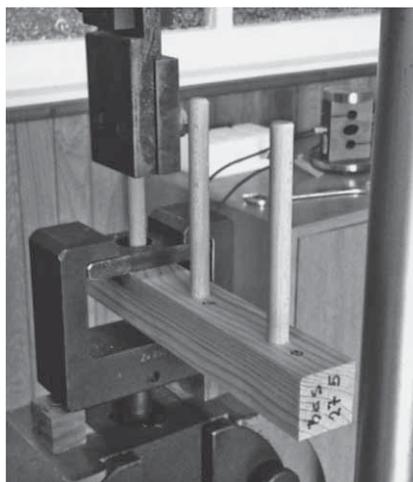


Figure 5 Manner of placing the testing specimen in the universal testing machine
Slika 5. Način postavljanja ispitnih uzoraka u univerzalni stroj za ispitivanje

Table 1 Descriptive statistics of embedded force for all groups of specimens

Tablica 1. Deskriptivna statistika izvlačne sile za sve skupine uzoraka

Sample code <i>Oznaka uzorka</i>	MC in specimens, % <i>Sadržaj vode u uzorcima,%</i>	Number of specimens <i>Broj uzoraka</i>	Embedded force / <i>Izvlačna sila</i>						
			Means, N <i>Srednja vrijednost, N</i>	Standard deviation, N <i>Standardna devijacija, N</i>	Min, N	Max, N	Q25, N	Median, N	Q75, N
1. Oven dry (heartwood) <i>1. osušeno (srž)</i>	0.0	30	1900.7	305.3	1335	2455	1622	1953,5	2185
2. Oven dry (sapwood) <i>2. osušeno (bjeljika)</i>	0.0	30	1920.3	394.8	1155	2840	1670	1832,5	2110
3. Magnesium Chloride (heartwood) <i>3. magnezijev klorid (srž)</i>	8.71	30	2901.1	300.0	2250	3510	2650	2935	3100
4. Magnesium Chloride (sapwood) <i>4. magnezijev klorid (bjeljika)</i>	9.03	24	2948.9	488.9	2130	4000	2620	2912,5	3237,5
5. Conditioned samples (heartwood) <i>5. kondicionirani uzorci (srž)</i>	10.05	30	2619.6	240.1	2270	3190	2420	2610	2810
6. Conditioned samples (sapwood) <i>6. kondicionirani uzorci (bjeljika)</i>	10.05	30	2679.6	588.4	1320	4080	2340	2625	3150
7. Sodium chloride (heartwood) <i>7. natrijev klorid (srž)</i>	12.41	30	3049.3	514.4	1950	4050	2675	3045	3440
8. Sodium chloride (sapwood) <i>8. natrijev klorid (bjeljika)</i>	13.70	28	2766.0	548.0	1785	4095	2295	2710	3147,5
All groups / <i>sve skupine</i>		232	2587.7	603.0	1155	4095	2207	2620	3000

samples exposed to magnesium chloride (heartwood and sapwood) and the samples exposed to sodium chloride (sapwood).

The statistical analysis showed no statistically significant difference between embedded forces for

absolutely dry samples (heartwood and sapwood). Namely, absolutely dry samples exhibited the lowest embedded force values (the average embedded force value for heartwood amounted to 1901 N and for sapwood to 1920.36 N), while the air conditioned sam-

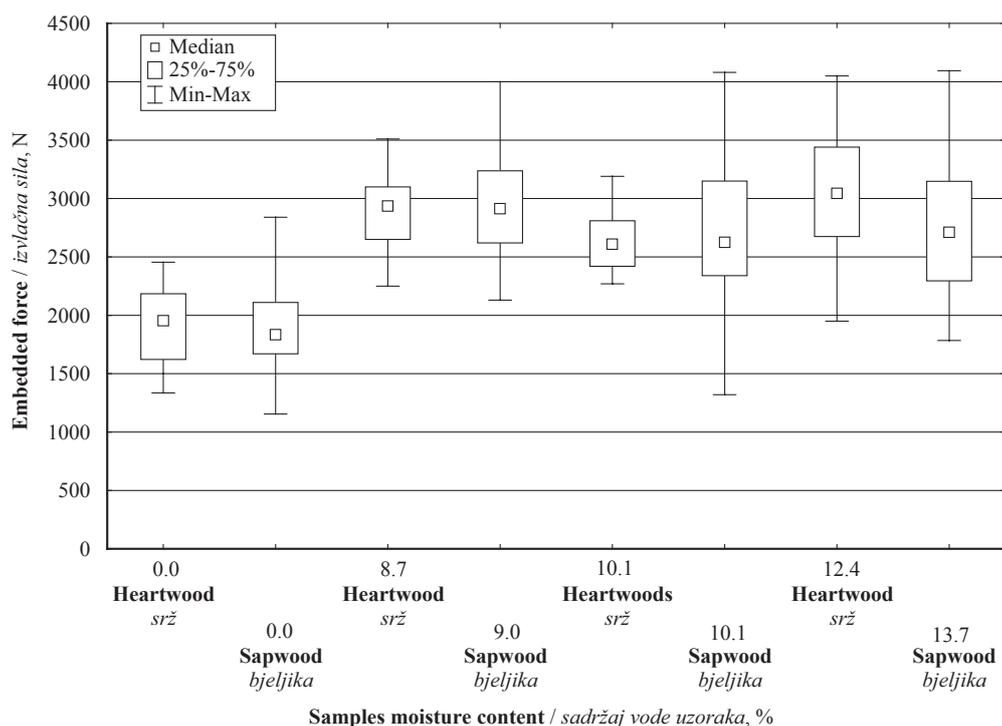


Figure 6 Comparison of embedded forces between groups of specimens conditioned to different MC

Slika 6. Usporedba izvlačne sile uzoraka kondicioniranih na različit sadržaj vode

ples (the average embedded force value amounted to 2649.06 N; for sapwood 2679.6 N and for heartwood 2619.6 N), and the samples exposed to sodium chloride (the average embedded force value amounted to 2907.7 N; for sapwood 2766.07 N and for heartwood 3049.33 N) exhibited the highest embedded force values.

A comparison between the results obtained by the statistical analysis of the embedded force values and the water content in the wood, and the statistical analysis of the embedded force values of the samples exposed to different levels of humidity, clearly shows that the embedded force increases as the humidity increases. An increase in air humidity resulted in an increased water content in the wood leading to wood swelling and changes in dimensions. This is why the embedded force values of the absolutely dry samples were much lower than those of other samples (the average embedded force for heartwood samples was 1900.73 N; the average embedded force for sapwood samples was 1920.36 N). The samples exposed to sodium chloride salts exhibited the highest embedded force values (the average of 3049.33 N). The samples with water content above 13.05 % exhibited the best embedded force values.

4 CONCLUSIONS

4. ZAKLJUČAK

Significant influence of moisture content on the embedded force or the strength of beech dowels welded in the Scots pine bases (specimens) was determined. There was a statistically significant increase in the embedded force between the oven dry specimens and specimens conditioned to average moisture content of 8.87 %. Embedded force slightly decreased for the samples conditioned to 10.05 % moisture content, and slightly increased for the samples conditioned to 13.05 % moisture content, but only for heartwood specimens, although these changes in embedded force were not statistically significant. Embedded forces for sapwood samples conditioned to 10.05 % and 13.7 % were almost the same.

Based on the obtained results, the moisture content of wood in the interval between 9 and 13 % does not have statistically significant effect on the embedded force and this moisture content of wood is optimal for dowel rotary welding. In the future research, the observed moisture content intervals should be expanded to determine at which water content embedded force decreases significantly.

Oven dry samples had the smallest embedded forces, due to increased brittleness of wood. Dowels welded in heartwood and sapwood did not show statistically significant difference in embedded force.

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Corresponding address:

IVAN ŽULJ, BSc

University of Zagreb
Faculty of Forestry
Svetošimunska 25, p.p. 422
HR-10002 Zagreb, CROATIA
e-mail: izulj@sumfak.hr