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Comparative Experimental Investigation of Two Different Levels of Heat-Treated Wood Properties

Eksperimentalno istraživanje svojstava drva toplinski obrađenoga pri dvjema temperaturama

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ABSTRACT • *This study examines the effects of heat treatment on the mechanical properties of four wood species: oak (Quercus petraea L), Scotch pine (Pinus sylvestris), chestnut (Castanea sativa) and cedar (Cedrus libani). Samples were subjected to heat treatment at 175 °C and 205 °C, and their bending strength, modulus of elasticity, compression strength, dynamic bending (shock) strength, column strength, and hardness were compared with untreated controls. Results revealed that wood species, treatment temperature and their interaction significantly influenced all mechanical properties. Oak consistently showed the highest performance, while cedar exhibited the lowest values. Heat treatment caused notable reductions in mechanical properties, with losses ranging from 0.2 % to 52.2 % at 175 °C and increasing further at 205 °C. The reduction is attributed to the thermal degradation of wood components such as cellulose, hemicellulose and lignin, leading to weakened cell walls and increased brittleness. Lower temperatures primarily produced a pre-treatment and drying effect, while higher temperatures intensified chemical degradation. Among the properties tested, bending strength, modulus of elasticity and hardness were most affected. The findings demonstrate that heat treatment significantly alters the mechanical performance of wood, and these changes must be considered in structural and engineering applications where strength and durability are critical factors. It has been determined that the mechanical property changes of needle-leaved and broad-leaved wood samples subjected to thermal treatment at both 175 °C and 205 °C in the same chamber are similar. It has been suggested that thermal treatment of both wood types could be carried out at a slightly higher chamber temperature (above 175 °C), thereby achieving a much closer thermal treatment effect for both wood types and potentially achieving significant energy savings.*

KEYWORDS: *heat treatment; wood type; mechanical properties; bending strength; modulus of elasticity; compressive strength; hardness*

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SAŽETAK • *U studiji je istražen utjecaj toplinske obrade na mehanička svojstva četiriju vrsta drva: hrasta (Quercus petraea L.), običnog bora (Pinus sylvestris), kestena (Castanea sativa) i cedra (Cedrus libani). Uzorci su podvrgnuti toplinskoj obradi pri 175 i 205 °C, a njihova čvrstoća na savijanje, modul elastičnosti, čvrstoća na tlak, čvrstoća na udar, čvrstoća izvijanja i tvrdoća uspoređeni su s istim svojstvima netretiranih kontrolnih uzoraka. Rezultati su pokazali da vrsta drva, temperatura obrade i njihova interakcija znatno utječu na sva mehanička svojstva. Hrastovina je dosljedno pokazala najbolja svojstva, dok su za cedrovinu zabilježena najlošija svojstva. Toplinska obrada prouzročila je znatno slabljenje mehaničkih svojstava s gubitcima u rasponu od 0,2 do 52,2 % za drvo obrađeno pri 175 °C, uz dodatno povećanje gubitaka na 205 °C. Slabljenje svojstava pripisuje se toplinskoj razgradnji drvnih komponenata poput celuloze, hemiceluloze i lignina, što dovodi do slabljenja staničnih stijenki i povećanja krhkosti drva. Niže temperature ponajprije su prouzročile efekt predobrade i sušenja, dok su više temperature pojačale kemijsku razgradnju. Među promatranim svojstvima najviše su oslabljeni čvrstoća na savijanje, modul elastičnosti i tvrdoća. Rezultati su pokazali da toplinska obrada znatno mijenja mehanička svojstva drva i te se promjene moraju uzeti u obzir u konstrukcijskim i građevinskim primjenama, u kojima su čvrstoća i trajnost ključni zahtjevi. Utvrđeno je da su promjene mehaničkih svojstava uzoraka crnogoričnoga i listopadnog drva podvrgnutih toplinskoj obradi pri 175 i 205 °C u istoj komori slične. Predloženo je da se toplinska obrada obiju vrsta drva provede na nešto višoj temperaturi komore (višoj od 175 °C), čime se postiže sličniji učinak toplinske obrade za obje vrste drva i ostvaruju se potencijalno veće uštede energije.*

KLJUČNE RIJEČI: *toplinska obrada; vrsta drva; mehanička svojstva; modul elastičnosti; čvrstoća na tlak; tvrdoća*

1 INTRODUCTION
1. UVOD

Current studies have generally shown that heat treatment at different temperatures and durations reduces bending strength, elastic modulus, compressive strength, and impact resistance. However, studies comparing the responses of both coniferous and broadleaf species to different temperature levels under the same conditions are quite limited. This study experimentally compares the effects of heat treatment at two different temperature levels (175 °C and 205 °C) on the mechanical properties of four different tree species – Scotch pine (*Pinus sylvestris*), Taurus cedar (*Cedrus libani*), oak (*Quercus petraea* L.), and chestnut (*Castanea sativa*) – in order to fill this gap. The novelty of the study lies in the simultaneous evaluation of both coniferous and broadleaf species under the same treatment conditions and the systematic presentation of changes in mechanical properties.

In this study, it was aimed to determine whether the heat treatment effect occurred in oak and Anatolian chestnut while the normal heat change occurred in the chemical structure of Scotch pine and cedar at 175 °C process at both temperature levels and heat treatment applications, and to determine what kind of a change occurred in Scotch pine and cedar exposed to heat treatment at higher temperatures while the normal heat change occurred in the chemical structure of oak and Anatolian chestnut at 205 °C. The hypothesis that temperature has an effect on both needle-leaved and broadleaved tree species was used as a starting point.

It is shown that the shore D hardness values and density values of rowan, chestnut, maple, common alder, Uludağ fir, willow, common hornbeam, Strandja oak and ash woods are reduced by heat treatment at 212 °C for 1 and 2 hours according to the ThermoWood method. (Türk *et al*., 2021).

In heat treatment methods, strength values decreased with increasing temperature. Compared to control samples, bending strength decreased by 35 % and 38 % in pine and beech samples heat-treated at 210°C using the hot air method, respectively. (Bayraktar *et al*., 2022).

Heat treatment significantly alters physical, chemical and mechanical properties of wood. Lower temperatures and duration of exposures resulted in some improvements in elastic constants probably due to lower EMC (Gültekin, 2024).

Changes in chemical composition due to the heat treatment included reducing carbohydrate content (particularly hemicelluloses) and decreasing the number of hydroxyls. The alterations were more pronounced for mature wood, making it more similar to juvenile control treated wood than to control mature wood. Also, more distinct alterations in the mechanical parameters measured in compression were observed (Broda *et al*., 2024).

The smallest effect of the heat treatment was determined at 130 °C for 2 h. Treatment temperature is highly correlated with all physical, mechanical and chemical properties of chestnut wood. In this case it can be said that temperature has greater influence on strength properties than time. For heat treatment process, 130 °C for 2 h should be applied where mechanical properties are important. However, 230 °C for 2 h should be used where physical properties are more important. Heat treated woods can be utilised using proper heat treatment time and temperature without any losses in strength values and chemical characteristics in areas where stability is important. Also, heat treatment can be considered as an environmentally friendly technique because no chemicals are involved during the process (Ates *et al*., 2010).

Thermal modification is an environmentally friendly technique that does not involve the use of toxic chemicals or generate harmful emissions. The increased durability of thermally modified wood can also contribute to the sustainable management of forest resources by reducing the demand for raw wood materials and promoting the use of fast growing and low-value wood species (Hasanagic *et al*., 2023).

Prior to a treatment temperature of 150 °C, the wood undergoes dehydration reactions. Elevated temperatures cause gradual water evaporation, reducing wood moisture content. Reduced moisture enhances the compactness and hardness of the wood, strengthening its mechanical properties compared to room temperature. Beyond 150 °C, continued dehydration leads to the gradual decomposition of hemicellulose in the cell wall, reducing its mechanical performance. The ultimate bearing capacity results of the compression test and bending test show that the ultimate bearing capacity of beech and maple is close to each other, while that of sylvestris Pine is poor. This is because sylvestris Pine is different from the other two kinds of softwood, and softwood is generally less dense and less hard (Zhou *et al*., 2024).

If overall changes in surface roughness were evaluated, the roughness of the sanded surface would increase after thermal modification in the case of pine and chestnut wood. In the case of the examined oak wood, there were no statistically significant changes in surface roughness after Thermo-Vacuum modification, despite a significant reduction in density and hardness. This was mainly due to the deep vessels present, which had a greater impact on surface roughness than microscopic grooves after sanding. Cedar wood showed no statistical differences in surface roughness before and after thermal modification (Adamcik *et al*., 2025).

Chemical transformations improve dimensional stability and resistance to biological agents such as fungi and insects, but at the same time, may lead to a weakening of some mechanical properties of wood, such as elasticity. Research from 2025 emphasises the importance of optimizing process parameters such as temperature, time, and treatment atmosphere to achieve a balanced improvement in properties while minimizing negative effects on the wood structure. Ongoing research aimed at a detailed understanding of chemical changes and their impact on the mechanical and physical properties of wood will help further improve the technology (Jancikova *et al*., 2025)

The release level of volatile organic compounds during high temperature heat treatment is much higher than that of conventional drying. Along with the heat treatment modification, the exhaust gas pollution purification treatment and absorption device is equipped to prevent the release of organic volatile compounds to pollute the air and harm human health (Cao *et al*., 2022).

Three wood species, Scotch pine, oak and chestnut samples were heat treated at four different conditions (150 °C / 5 h, 170 °C / 4 h, 190 °C / 3 h, 210 °C / 2 h) and these samples were tested in three different climatic conditions (20 °C / 65 %, 40 °C / 35 %, 10 °C / 50 %), respectively. According to the results of the study, it was determined that the highest values of bending strength and modulus of elasticity were obtained at the lowest temperature heat treatment (150 °C / 5 h) and 40 °C / 35 % climate condition. It was determined that the resistance values decreased as the heat treatment temperature increased (Altunok *et al*., 2023).

The effect of heat treatment temperature on the modulus of elasticity in bending of Scotch pine wood test samples was found to be significant. The highest modulus of elasticity value was determined in samples heat treated at 170 °C, while the lowest was determined in samples heat treated at 210 °C. These decreases in modulus of elasticity may have occurred due to structural damages (thermal decomposition) in wood material components as a result of high heat treatment temperature, as well as mass decrease and density losses (Bayraktar, 2023).

Heat-treated wood has a more aesthetic appearance and is an environmentally friendly, renewable material. One of the negative properties of heat-treated wood is its low mechanical strength. In the literature, it has been reported that impregnation of wood material with some chemicals before heat treatment reduces its thermal degradation (Perçin *et al*., 2023).

Aydemir *et al.* (2009), reported that heat treatment should be considered as an alternative method of wood preservation and wood modification. It was recommended that the heat treatment temperature should be above 200 °C when better protection against the external environment or decay is desired, and below 200 °C for indoor use.

According to the results obtained from the physical, mechanical, morphological and thermal properties of Beech and Oak woods after heat treatment in Bürüç *et al*. (2019), it was found that all mechanical properties and density, as well as water absorption values decreased with heat treatment.

Doruk and Perçin (2010) determined that the losses in the mechanical properties of the wood material modified at low temperatures were less. In the samples exposed to heat treatment at 130 °C, 165 °C and 200 °C for 2, 6 and 10 hours, the least decrease in mechanical properties was found in the samples treated at 130°C for 2 hours and it was determined that the mechanical resistance decreased as the time of heat treatment increased.

Kaymakci and Bayram (2021) found in their study that heat treatment applications above 150 °C or 4 hours are not recommended for structural uses as they cause a decrease in mechanical properties.

Perçin *et al*. (2017) reported that bending strength and compressive strength parallel to the fibres increased at low temperatures due to some drying, while these resistances decreased at high oven temperatures.

Xu *et al*. (2019) performed thermal modification on test samples obtained from white oak (*Quercus alba* L.) wood by heat treatment at 160 °C, 180 °C and 200 °C for 3, 6 and 9 hours. It was observed that *MOR* values started to decrease as the temperature increased. While the *MOR* value was 203.85 MPa in the control samples, the minimum decrease was 202.36 MPa in the samples treated at 160°C for 3 hours and the maximum decrease was 169.28 MPa in the samples treated at 200 °C for 9 hours.

Gündüz *et al*. (2011) applied 180 °C and 2 hours heat treatment to tannin and tannin-free samples prepared from chestnut wood. The highest bending strength was obtained in tannin-control samples and the lowest in tannin-free-heat-treated samples. The compressive strength was 51.2 N/mm^2 in control samples, the highest 58.22 N/mm^2 in tannin-control samples and 55.12 N/mm^2 in tannin-treated samples. It was found that the bending and compressive strengths decreased in the heat-treated samples and tannin reduced this decrease.

As the weight loss increases, hardness values decrease on the tangential and radial surfaces and increase slightly on the cross-sectional surface. In the group treated at 220 °C, there was a decrease of approximately 18 % in hardness values on the tangential and radial surfaces. According to these data, considering the expansion percentages and hardness value data, the temperature range between 200 °C and 220 °C can be recommended as the appropriate treatment range for yellow pine timber (Bal *et al*., 2016).

Heat treatment causes the loss of strength of wood. Therefore, heat-treated wood should not be used where strength is a dominant factor (Toker *et al*., 2016).

Korkut (2016) showed that all mechanical properties of the heat-treated sessile oak samples tested in his study were slightly reduced compared to the control samples. Heat treatment temperature is not the only parameter contributing to the reduction of mechanical properties; weight loss is directly linked to the treatment time. As the mechanical properties of sessile oak are reduced as a result of heat treatment, it is recommended that such units should not be used in construction applications.

An increase in the modulus of elasticity was recognised after heat treatment during the bending strength test. Changes and/or modifications in the main wood components influence the mechanical properties of the heat treatment. However, heat-treated timber shows potential for use in construction. Since *MOE* is usually the most critical parameter for a construction, with higher stiffness resulting in lower deflection for a given load, heat treatment does not seem to reduce the potential for construction applications. However, it is important to carefully evaluate the stresses and some practical consequences in a construction when using heat-treated timber, because the effect of heat treatment on different strength properties is not proportional. Furthermore, further test work is required to study the effect of heat treatment in long-term and repeated loadings for internal and external conditions (Michiel *et al*., 2007).

Another phenomenon that may affect the strength properties of wood after heat treatment is the thermoplastic property of wood. Above a certain temperature the physical properties of haemicelluloses (127-235 °C), lignin (167-217 °C) and cellulose (231-253 °C) change to a rubber or plastic state. Thermal softening of wood as a whole occurs at temperatures above 200 °C, but steaming lowers the softening point (180 °C) due to water acting as a plasticiser. The thermal behaviour of lignin and hemicelluloses appears to be constrained by interactions due to secondary intermolecular bonding with cellulose. The degradation of hemicelluloses during the hydro-thermolysis phase affects this secondary bonding, which allows the remaining hemicelluloses and lignin to be plasticised. During the cooling phase, these components harden again, and the molecular polymer structure may change. This probably influences the interaction between the main components of the wood, affecting its strength properties (Michiel *et al*., 2007).

It can be said that both *MOR* and *MOE* values decrease with the increase of the temperature and time of heat treatment. The maximum decreases to all parameters were recorded with the treatment at 160 °C for 9 h. The lowest modulus of rupture value was obtained from samples treated at the 205 °C for 12 h (43.10 N/mm^2). The lowest modulus of elasticity value was obtained from the same heat treatment conditions. Heat treatment decreases mechanical properties of wood, but it increases the properties of dimensional stability and the biological durability of wood (Yapıcı *et al*., 2012).

In this study, the wood species were heat treated for 3 hours at low temperatures determined at both levels. At 175 °C, it was aimed to determine whether a normal thermal change occurred in the chemical structure of Scotch pine and cedar wood, while a heat treatment effect occurred in oak and chestnut, and at 205 °C, while a normal thermal change occurred in the chemical structure of oak and chestnut, it was aimed to determine what kind of extra change occurred in Scotch pine and cedar exposed to heat treatment at higher temperature.

2 MATERIALS AND METHODS
2. MATERIJALI I METODE

In this study, first class sessile oak (*Quercus petrea* L), chestnut (*Castenea sativa*), taurus cedar (*Cedrus libani*), Scotch pine (*Pinus sylvestris*) timbers, which are widely used in the woodworking industry and are locally produced, were randomly obtained from Ankara Keresteciler Sitesi.

2.1 Preparation of test samples
2.1. Priprema ispitnih uzoraka

Four different types of wooden slats of draft sizes obtained randomly from the market were heat treated at 175 °C and 205 °C in the same process, and test and measurement samples were prepared by cutting the test and measurement samples from these materials in the sizes stipulated by the standards in the size and number given in Table 1.

2.2 Heat treatment
2.2. Toplinska obrada

In the first stage, draft pieces from each of the four wood species sufficient for the samples in Table 1 were placed in the heat treatment furnace with laths between them (Figure 1), and heat treatment was applied at 175 °C.

In the second step, draft pieces from each of the four wood species sufficient for the samples in Table 1 were placed in the heat treatment furnace with laths

Table 1 Type of wood to be heat treated and research test/measurement pattern, standards.
Tablica 1. Vrste drva koje su toplinski obrađene i postupak ispitivanja/mjerenja u istraživanju te standardi

	Properties, dimensions and number of wooden specimens *Svojstva, dimenzije i broj uzoraka drva*				**Treatment of samples** *Vrsta obrade*		
Wood type *Vrsta drva*	**Test / measurement** *Ispitivanje/mjerenje*	**Standards** *Standardi*	**Dimensions, mm** *Dimenzije, mm*	**Total sample** *Ukupno uzoraka*	**Control** *Kontrolni uzorci*	**175 °C**	**205 °C**
Cedar Skotch pine Oak Chestnut *cedrovina borovina hrastovina kestenovina*	Bending strength *čvrstoća na savijanje*	TS ISO 13061-3, 2021 TS 13061-4 , 2014	30×60×960	15	5	5	5
	Elastical modulus *modul elastičnosti*	TS ISO 13061-3, 2021 TS 13061-4 , 2014	30×60×960	15	5	5	5
	Compression strength *čvrstoća na tlak*	TS EN 408 + A1, 2014	20×20×30	15	5	5	5
	Hardness *tvrdoća*	TS ISO 13061-12 [96] , 2021	20×50×50	15	5	5	5
	Column strength *čvrstoća na izvijanje*	TS EN 408 + A1 , 2014	30×60×600	15	5	5	5
	Shock strength *čvrstoća na udarac*	TS ISO 13061-10 , 2021	20×20×350	15	5	5	5
	Total / *Ukupno*			90	30	30	30

Note: The number of samples given above is valid only for one wood species, the same number of samples were prepared for 4 wood species (90 × 4 = 360 pieces).
Napomena: Navedeni broj uzoraka vrijedi samo za jednu vrstu drva. Za sve četiri vrste drva pripremljen je jednak broj uzoraka (90 × 4 = 360 komada).

Figure 1 Stacking in heat treatment furnace
Slika 1. Slaganje uzoraka u komoru za toplinsku obradu

between them, and heat treatment was applied at 205 °C. The heat treatment in both steps was carried out in the process shown in Figure 2 below.

Drying of wood: By gradually increasing the temperature up to 130 °C, the wood material is dried for a long time.

Heat treatment application: First, pre-heat treatment at an increasing temperature and then heat treatment at constant temperature of 175 °C and 205 °C. In this process, water vapour is sprayed into the furnace for 15 seconds per minute, preventing the wood from catching fire and reducing the internal stress (Figure 3).

Cooling: Cooled by spraying water until the temperature drops to 30 °C.

2.3 Statistical analysis
2.3. Statistička analiza

Under the same chamber conditions, the effect of heat treatment on specific mechanical properties of coniferous tree species (Scots pine and cedar) and broadleaf tree species (oak and chestnut) was determined at two different temperatures (175 °C and 205 °C). When the effect of tree species and treatment type on mechanical properties was significant, a homogeneity test was performed at a significance level of $p \leq 0.05$ using a t-test. When the effect of tree species and processing types on mechanical properties was found to be significant, Duncan's test was applied to determine the homogeneity groups.

3 RESULTS AND DISCUSSION
3. REZULTATI I RASPRAVA

Some of the mechanical property changes experimentally obtained from the control and heat-treated samples at the end of heat treatment of four wood species at two different temperature levels (175 °C – 205 °C) are given below.

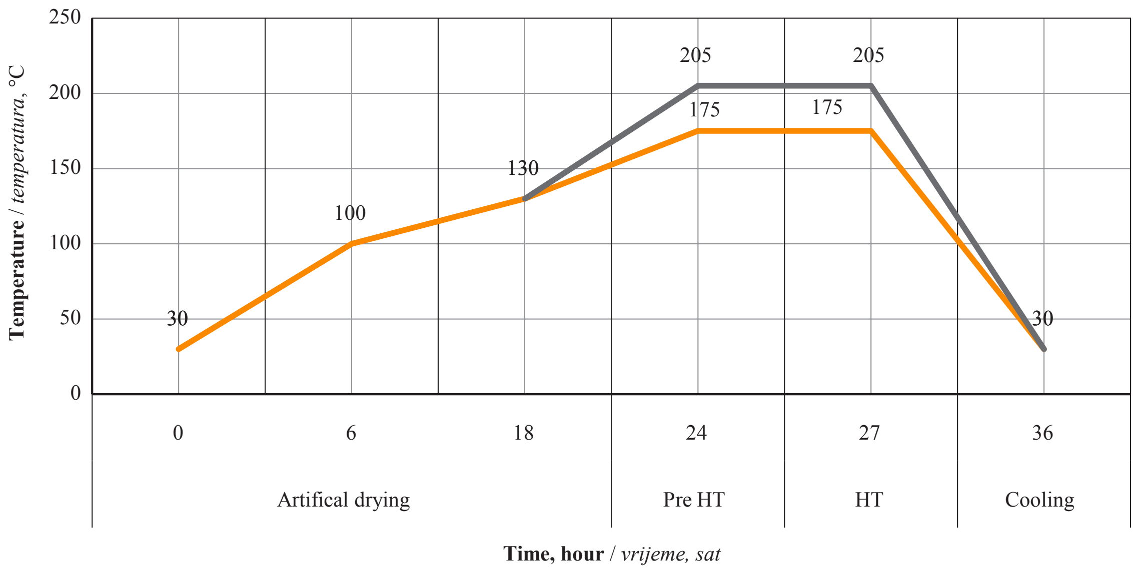

Figure 2 Heat treatment graph
Slika 2. Grafikon procesa toplinske obrade

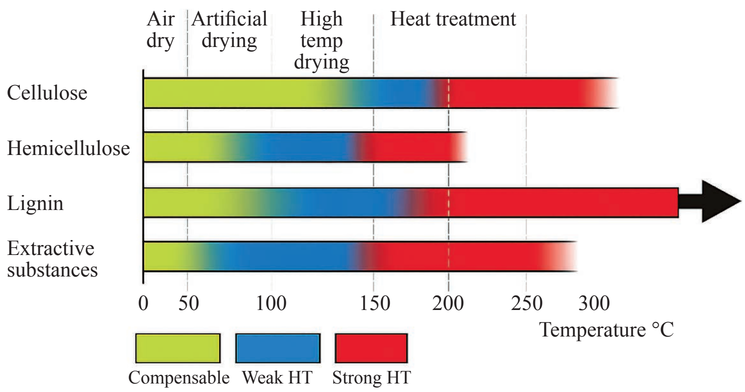

Figure 3 Behaviour of wood basic components in the heat treatment process (Sundqvist *et al*., 2004)
Slika 3. Ponašanje osnovnih komponenata drva u procesu toplinske obrade (Sundqvist i sur., 2004.)

3.1 Bending strength change
3.1. Promjena čvrstoće na savijanje

To determine the variables causing variation in the bending strength values of heat treatment at two different temperature levels and four wood species, multiple variance analysis was applied, and the results are presented in Table 2.

The analysis of variance in Table 2 shows that the effects of wood type, treatment type and their binary interactions on bending strength are significant. It was found that the heat treatment process contributed the highest to the change in bending strength, then the wood and the lowest to the binary interaction.

The averages of the bending strength values of the samples of four wood species after control and heat treatment, the averages of the interaction of bending strength with wood and heat treatment and the homogeneity groups of these averages are given in Table 3.

In Table 3, in terms of wood species, the highest bending strength was found in oak, followed by Scotch pine, chestnut and cedar, respectively. In terms of treatment, the highest bending strength was found in control, then in samples heat treated at 175 °C and 205 °C, respectively. Compared to the bending strength of the control samples, the bending strength of each wood species decreased in the heat-treated samples, and the bending strength decreased further as the heat treatment temperature increased. It can be said that the decrease in bending strength is due to the degradation of wood cell components (cellulose, lignin and hemicellulose) depending on the process temperature of the heat treatment. At the same time, in the dual interaction of these two factors, the highest bending bending strength was found in the control group of oak samples, then in the control group of Scotch pine and heat treated oak samples -175 °C and Skotch pine – 175 °C. The lowest bending bending strength was obtained in Cedar – 175 samples. In the wood-treatment interaction, it can be said that the reason for the highest bending bending strength in oak – 175 °C samples is that the cabin temperature of 175 °C is low for broadleaf oak. It creates an effect at the level of pre-heat treatment, and the heat treatment effect at this temperature is not sufficient for cellular degradation. In the 205 °C heat treatment processes, it is seen that Scotch pine and cedar lost more bending strength and it can be said that this is due to the fact that coniferous samples undergo more degradation at high temperature causing more disintegration and collapse of cell walls. This result is also supported by the research results of Xu *et al*. (2019); Michiel *et al*. (2007).

Table 2 Multiple variance analysis for bending strength
Tablica 2. Višestruka analiza varijance za čvrstoću na savijanje

K value *K-vrijednost*	**Source** *Izvor*	**Degrees of freedom** *Stupanj slobode*	**Sum of squares** *Zbroj kvadrata*	**Mean square** *Srednji kvadrat*	**F value** *F-vrijednost*	**P <0.05**
2	A (Wood)	3	4702.225	1567.408	183.5499	0.0000
4	B (Process)	2	9211.451	4605.726	539.3492	0.0000
6	AB	6	3391.412	565.235	66.1914	0.0000
-7	Error	48	409.892	8.539		
	Total	59	17714.980			

Table 3 Bending strength (N/mm^2) comparisons and homogeneity groups in terms of wood species and heat treatment
Tablica 3. Usporedbe čvrstoće na savijanje (N/mm^2) i skupine homogenosti s obzirom na vrstu drva i toplinsku obradu

Wood type *Vrsta drva*	**Averages, N/mm^2** *Srednja vrijednost,* N/mm^2	**HG.**
Oak (O)	64.79	A
Scotch pine (Sp)	58.08	B
Chestnut (Ch)	47.88	C
Cedar (C)	41.93	D
LSD = 2.135, α = 0.050		

Process *Obrada*	**Averages, N/mm^2** *Srednja vrijednost,* N/mm^2	**HG.**
Control	69.82	A
175 °C heat treated	49.59	B
205 °C heat treated	40.10	C
LSD = 1.849, α = 0.050		

Wood type + process interaction *Interakcija vrste drva i obrade*	**Averages, N/mm^2** *Srednja vrijednost,* N/mm^2	**HG.**
O+Control	86.186	A
Sp+Control	68.472	B
O+175 °C	66.086	BC
Sp+175 °C	65.892	BC
C+Control	62.836	CD
Ch+Control	61.768	D
O+205 °C	42.096	E
Ch+175 °C	41.950	E
Ch+205 °C	39.930	E
Sp+205 °C	39.884	E
C+205 °C	38.510	E
C+175 °C	24.438	F
LSD = 3.698, α = 0.050		

3.2 Elastic modulus change in bending
3.2. Promjena modula elastičnosti pri savijanju

To determine the variables causing variation in the bending strength values of four wood species and two different heat treatment temperatures, multiple variance analysis was applied, and the results are presented in Table 4.

The analysis of variance in Table 4 shows that the effects of wood type, treatment type and their binary interactions on the elastical modulus are significant. It was found that the heat treatment process contributed the highest to the change in the elastical modulus, then the wood and the lowest to the binary interaction.

The averages of the changes in the elastical modulus values of the samples of four wood species after control and two heat treatments, the averages of the interaction of wood and heat treatment in terms of the effect on the elastical modulus and the homogeneity groups of these averages are given in Table 5.

In Table 5, in terms of wood species, the highest elastical modulus was found in oak and Scotch pine, followed by chestnut and cedar, respectively. In terms of heat treatment, the highest elastical modulus was found in the control, followed by 175 °C and 205 °C samples, respectively. Compared to the elastical modulus in the control samples, the elastical modulus of each wood species decreased in the heat-treated samples, and the elastical modulus decreased further as the heat treatment temperature increased. It can be said that the decrease in the elastical modulus is due to the degradation of wood cell components (cellulose, lignin and hemicellulose) depending on the process temperature of the heat treatment. At the same time, in the dual interaction of these two factors, the highest elastical modulus was found in oak-control samples, followed by oak – 175 °C. The lowest elastical modulus was obtained in cedar – 205 °C samples. In the wood-treatment interaction, it can be said that the reason for the highest elastical modulus in oak-175 °C samples is that the cabin temperature of 175 °C is low for broadleaf oak. It creates an effect at the level of pre-heat treatment and the heat treatment effect at this temperature is not sufficient for cellular degradation. In the 205 °C heat treatment processes, Scotch pine and cedar lost more elasticity (became brittle), and it can be said that this is due to the fact that coniferous samples undergo more degradation at high temperature causing more collapse in the cell walls. This result is also supported by the research results of Xu *et al*. (2019); Michiel *et al*. (2007); Gültekin (2024); Jancikova *et al*. (2025).

Table 4 Multiple variance analysis for elastical modulus
Tablica 4. Višestruka analiza varijance za modul elastičnosti

K value *K-vrijednost*	Source *Izvor*	Degrees of freedom *Stupanj slobode*	Sum of squares *Zbroj kvadrata*	Mean square *Srednji kvadrat*	F value *F-vrijednost*	P <0.05
2	A (Wood)	3	813505335.784	271168445.261	109.2641	0.0000
4	B (Process)	2	670911421.878	335455710.939	135.1679	0.0000
6	AB	6	863073230.740	143845538.457	57.9608	0.0000
-7	Error	48	119125015.034	2481771.147		
	Total	59	2466615003.436			

Table 5 Elastical modulus (N/mm²) comparisons and homogeneity groups in terms of wood species and heat treatment
Tablica 5. Usporedbe modula elastičnosti (N/mm²) i skupine homogenosti s obzirom na vrstu drva i toplinsku obradu

Wood type *Vrsta drva*	Averages, N/mm² *Srednja vrijednost,* N/mm²	HG.
Oak (O)	21510	A
Scotch pine (Sp)	21190	A
Chestnut (Ch)	14780	B
Cedar (C)	13340	C
LSD = 1151, α = 0.050		

Process *Obrada*	Averages, N/mm² *Srednja vrijednost,* N/mm²	HG.
Control	22040	A
175 °C heat treated	17170	B
205 °C heat treated	13900	C
LSD = 996.8, α = 0.050		

Wood type + process interaction *Interakcija vrste drva i obrade*	Averages, N/mm² *Srednja vrijednost,* N/mm²	HG.
O+Control	34130	A
O+175 °C	25110	B
Sp+Control	22760	C
O+205 °C	16650	D
Sp+175 °C	16420	D
C+Control	16050	DE
Ch+Control	15210	DE
Ch+175 °C	14890	DEF
Ch+205 °C	14230	EFG
Sp+205 °C	13020	FGH
C+175 °C	12270	GH
C+205 °C	11700	H
LSD = 1994, α = 0.050		

3.3 Compression strength change
3.3. Promjena čvrstoće na tlak

To determine the variables causing variation in the compression strength values of four wood species and two different heat treatment temperatures, multiple variance analysis was applied, and the results are presented in Table 6.

The analysis of variance in Table 6 shows that the effects of wood species, treatment type and their binary interactions on compression strength are significant. It was determined that the highest contribution to the change in compression strength was made by the wood species, then by the heat treatment and the lowest by the binary interaction.

The averages of the changes in the compression strength values of the samples of four wood species after control and two heat treatments, the averages of the interaction of wood and heat treatment in terms of the effect on compression strength and the homogeneity groups of these averages are given in Table 7.

In Table 7, in terms of wood species, the highest compression strength was found in oak, followed by chestnut cedar and Scotch pine samples, respectively. Compared to the compression strength in the control samples, the compression strength of each wood species decreased in the heat-treated samples and the compression strength decreased further as the heat treatment temperature increased. It can be said that the decrease in compression strength is due to the degradation of wood cell components (cellulose, lignin and hemicellulose) depending on the process temperature of the heat treatment.

At the same time, in the dual interaction of these two factors, the highest compression strength was found in oak control and heat-treated oak samples. The lowest compression strength was found in Scotch pine – 205 °C samples. In the wood-treatment interaction, it can be said that the reason for the highest compression strength in oak samples is that the cabin temperature of 175 °C is low for broadleaf oak, and the heat treatment effect at this temperature is not sufficient for cellular degradation. The low temperature (175 °C) caused pre-heat treatment with a drying effect. These results are supported by the results of Gündüz *et al*. (2011), Michiel *et al*. (2007) and Broda *et al*. (2024).

In the 205 °C heat treatment processes, it is seen that Scotch pine and cedar lost more resistance, and it can be said that this is due to the fact that coniferous samples undergo more degradation at high temperature causing more collapse in the cell walls.

Table 6 Multiple variance analysis compression strength
Tablica 6. Višestruka analiza varijance za čvrstoću na tlak

K value *K-vrijednost*	Source *Izvor*	Degrees of freedom *Stupanj slobode*	Sum of squares *Zbroj kvadrata*	Mean square *Srednji kvadrat*	F value *F-vrijednost*	P <0.05
2	A (Wood)	3	4286.472	1428.824	352.8743	0.0000
4	B (Process)	2	158.385	79.192	19.5580	0.0000
6	AB	6	58.698	9.783	2.4161	0.0403
-7	Error	48	194.357	4.049		
	Total	59	4697.912			

Table 7 Compression strength (N/mm^2) comparisons and homogeneity groups in terms of wood species and heat treatment
Tablica 7. Usporedbe čvrstoće na tlak (N/mm^2) i skupine homogenosti s obzirom na vrstu drva i toplinsku obradu

Wood type *Vrsta drva*	Averages, N/mm^2 *Srednja vrijednost,* N/mm^2	HG.
Oak (O)	63.37	A
Chestnut (Ch)	45.62	B
Cedar (C)	44.98	B
Scotch pine (Sp)	41.81	C
LSD = 1.470, α = 0.050		

Process *Obrada*	Averages, N/mm^2 *Srednja vrijednost,* N/mm^2	HG.
Control	51.07	A
175 °C heat treated	48.64	B
205 °C heat treated	47.12	C
LSD = 1.273, α = 0.050		

Wood type + process interaction *Interakcija vrste drva i obrade*	Averages, N/mm^2 *Srednja vrijednost,* N/mm^2	HG.
O+Control	63.00	A
O+175 °C	62.86	A
O+205 °C	62.86	A
Ch+175 °C	49.42	B
C+175 °C	46.58	C
Ch+205 °C	45.63	CD
C+205 °C	44.22	CDE
C+Control	44.14	CDE
Sp+Control	44.03	DE
Ch+Control	41.81	EF
Sp+175 °C	41.72	EF
Sp+205 °C	39.68	F
LSD = 2.547, α = 0.050		

3.4 Dynamic bending (shock) strength change
3.4. Promjena čvrstoće na udarac

To determine the variables causing variation in the shock strength values of four wood species and two different heat treatment temperatures, multiple variance analysis was applied, and the results are presented in Table 8.

The analysis of variance in Table 8 shows significant effects of wood species, treatment type and their binary interactions on shock strength. It was found that the highest contribution to the change in shock strength was made by wood type and heat treatment in equal proportions and the lowest by their interaction.

The averages of the changes in the shock strength values of the samples of four wood species after control and two heat treatments, the averages of the wood and heat treatment interaction in terms of the effect on shock strength and the homogeneity groups of these averages are given in Table 9.

In Table 9, in terms of wood species, the highest shock strength was found in oak, followed by chestnut, Scotch pine and cedar samples, respectively. Compared to the shock strength in the control samples, the shock strength of each wood species was found to decrease in the heat treated samples and the shock strength decreased further as the heat treatment temperature increased. It can be said that the decrease in shock strength is due to the degradation of wood cell components (cellulose, lignin and hemicellulose) depending on the process temperature of the heat treatment. These results are supported by the results of Gündüz *et al.* (2011) and Michiel *et al.* (2007). At the same time, in the dual interaction of these two factors, the highest shock strength was found in oak control and oak – 175 °C samples. The lowest shock strength was obtained in cedar samples. In the wood-treatment interaction, it can be said that the reason for the highest shock strength in oak samples is that the cabin temperature of 175 °C is low for broadleaf oak and the heat treatment effect at this temperature is not sufficient for cellular degradation (cellulose and lignin). The low temperature (175 °C) created a pre-heat treatment with a drying effect. In the 205 °C heat treatment processes, it is seen that Scotch pine and cedar lost more strength and it can be said that this is due to the fact that coniferous samples undergo more degradation at high temperature and causing collapse in the cell walls.

3.5 Column strength change
3.5. Promjena čvrstoće na izvijanje

To determine the variables causing variation in the column strength values of four wood species and two different heat treatment temperatures, multiple variance analysis was applied, and the results are presented in Table 10.

Table 8 Multiple variance analysis for dynamic bending (shock) strength
Tablica 8. Višestruka analiza varijance za čvrstoću na udar

K value *K-vrijednost*	Source *Izvor*	Degrees of freedom *Stupanj slobode*	Sum of squares *Zbroj kvadrata*	Mean square *Srednji kvadrat*	F value *F-vrijednost*	P <0.05
2	A (Wood)	3	4809.807	1603.269	123.8336	0.0000
4	B (Process)	2	2380.756	1190.378	123.8336	0.0000
6	AB	6	1000.389	166.732	12.8780	0.0000
-7	Error	48	621.454	12.947		
	Total	59	8812.406			

Table 9 Dynamic bending (shock) strength averages and Duncan test homogeneity groups
Tablica 9. Prosjeci čvrstoće na udarac i skupine homogenosti Duncanova testa

Wood type *Vrsta drva*	Averages, kJ/m² *Srednja vrijednost,* kJ/m²	HG.
Oak (O)	44.85	A
Chestnut (Ch)	39.82	B
Scotch pine (Sp)	36.50	C
Cedar (C)	20.89	D
LSD = 2.629, α = 0.050		

Process *Obrada*	Averages, kJ/m² *Srednja vrijednost,* kJ/m²	HG.
Control	43.74	A
175 °C heat treated	34.37	B
205 °C heat treated	28.43	C
LSD = 2.277, α = 0.050		

Wood type + process interaction *Interakcija vrste drva i obrade*	Averages, kJ/m² *Srednja vrijednost,* kJ/m²	HG.
O+Control	61.06	A
O+175 °C	44.78	B
Ch+Control	44.41	B
Sp+Control	42.87	BC
Ch+175 °C	38.78	CD
Ch+205 °C	36.28	D
Sp+175 °C	35.16	DE
Sp+205 °C	31.47	EF
O+205 °C	28.70	FG
C+Control	26.59	G
C+175 °C	18.77	H
C+205 °C		H
LSD = 4.554, α = 0.050		

Table 10 Column strength multiple variance analysis
Tablica 10. Višestruka analiza varijance za čvrstoću na izvijanje

K value *K-vrijednost*	**Source** *Izvor*	**Degrees of freedom** *Stupanj slobode*	**Sum of squares** *Zbroj kvadrata*	**Mean square** *Srednji kvadrat*	**F value** *F-vrijednost*	**P <0.05**
2	A (Wood)	3	3339.197	1113.066	109.2308	0.0000
4	B (Process)	2	2753.601	1376.801	135.1125	0.0000
6	AB	6	3542.337	590.389	57.9380	0.0000
-7	Error	48	489.121	10.190		
	Total	59	10124.256			

Table 11 Column strength averages and Duncan test homogeneity groups
Tablica 11. Prosjeci čvrstoće na izvijanje i skupine homogenosti Duncanova testa

Wood type *Vrsta drva*	**Averages, N/mm²** *Srednja vrijednost,* N/mm²	**HG.**
Oak (O)	43.57	A
Scotch pine (Sp)	42.93	A
Chestnut (Ch)	29.94	B
Cedar (C)	27.02	C
LSD = 2.332, α = 0.050		

Process *Obrada*	**Averages, N/mm²** *Srednja vrijednost,* N/mm²	**HG.**
Control	44.65	A
175 °C heat treated	34.78	B
205 °C heat treated	28.16	C
LSD = 2.020, α = 0.050		

Wood type + process interaction *Interakcija vrste drva i obrade*	**Averages, N/mm²** *Srednja vrijednost,* N/mm²	**HG.**
O+Control	69.14	A
O+175 °C	50.87	B
Sp+Control	46.11	C
O+205 °C	33.72	D
Sp+175 °C	33.26	D
C+Control	32.52	DE
Ch+Control	30.81	DE
Ch+175 °C	30.16	DEF
Ch+205 °C	28.84	EFG
Sp+205 °C	26.38	FGH
C+175 °C	24.85	GH
C+205 °C	23.69	H
LSD = 4.040, α = 0.050		

The analysis of variance in Table 10 shows that the effects of wood type, treatment type and their binary interactions on the column strength are significant. It was found that the highest contribution to the change in column strength was made by heat treatment, followed by wood type and the lowest by the binary interaction.

The averages for the change in column strength values, the averages for the interaction of wood and heat treatment in terms of the effect on column strength and the homogeneity groups of these averages are given in Table 11.

In Table 11, in terms of wood species, the highest column strength was found in oak and Scotch pine, followed by chestnut and cedar samples, respectively. Compared to the column strength in the control samples, the column strength of each wood species decreased in the heat treated samples and the column strength decreased further as the heat treatment temperature increased. It can be said that the decrease in column strength is due to the degradation of wood cell components (cellulose, lignin and haemicellulose) depending on the process temperature of heat treatment. These results are supported by the results of Gündüz *et al*. (2011) and Michiel *et al*. (2007). At the same time, in the dual interaction of these two factors, the highest column strength was found in the oak control group and oak – 175 °C samples. The lowest column strength was obtained in heat treated cedar samples. In the wood-treatment interaction, it can be said that the reason for the highest column strength in oak samples is that the cabin temperature of 175 °C is low for broadleaf oak and the heat treatment effect at this temperature is not sufficient for cellular degradation (cellulose and lignin). The low temperature (175 °C) created a pre-heat treatment causing a drying effect. In the 205 °C heat treatment processes, it is seen that Scotch pine and cedar lost more resistance and it can be said that this is due to the fact that coniferous samples undergo more degradation at high temperature causing collapse in the cell walls. These results are supported by the results Ates *et al*. (2010).

3.6 Hardness change
3.6. Promjena tvrdoće

To determine the variables causing variation in the hardness values of four wood species and two different heat treatment temperatures, multiple variance analysis was applied, and the results are presented in Table 12.

In the analysis of variance in Table 12, it is seen that the effects of wood type, treatment type and their binary interactions on hardness are significant. It was determined that the highest contribution to the change in hardness was made by heat treatment, followed by the binary interaction and the lowest by wood species.

Table 12 Hardness multiple variance analysis
Tablica 12. Višestruka analiza varijance za tvrdoću

K value *K-vrijednost*	**Source** *Izvor*	**Degrees of freedom** *Stupanj slobode*	**Sum of squares** *Zbroj kvadrata*	**Mean square** *Srednji kvadrat*	**F value** *F-vrijednost*	**P <0.05**
2	A (Wood)	3	6.429	2.143	0.096	0.0000
4	B (Process)	2	17.605	8.802	91.756	0.0000
6	AB	6	5.172	0.862	8.985	0.0000
-7	Error	48	4.605	0.096		
	Total	59	33.811			

Table 13 Hardness averages and Duncan test homogeneity groups
Tablica 13. Prosjeci tvrdoće i skupine homogenosti Duncanova testa

Wood type *Vrsta drva*	**Averages, N/mm²** *Srednja vrijednost,* N/mm²	**HG.**
Oak (O)	2.473	A
Scotch pine (Sp)	1.853	B
Cedar (C)	1.767	BC
Chestnut (Ch)	1.612	C
LSD = 0.2264, α = 0.050		

Process *Obrada*	**Averages, N/mm²** *Srednja vrijednost,* N/mm²	**HG.**
Control	2.641	A
175 °C heat treated	1.809	B
205 °C heat treated	1.330	C
LSD = 0.1961, α = 0.050		

Wood type + process interaction *Interakcija vrste drva i obrade*	**Averages, N/mm²** *Srednja vrijednost,* N/mm²	**HG.**
O+Control	3.616	A
C+Control	2.754	B
O+175 °C	2.462	BC
Sp+Control	2.180	CD
Ch+Control	2.014	D
Sp+175 °C	1.810	DE
Sp+205 °C	1.570	EF
Ch+175 °C	1.568	EF
C+175 °C	1.394	FG
O+205 °C	1.342	FG
Ch+205 °C	1.254	FG
C+205 °C	1.154	G
LSD = 0.3921, α = 0.050		

Table 14 Change in physical properties of wood species according to heat treatment
Tablica 14. Promjena fizičkih svojstava drva ovisno o toplinskoj obradi

Mechanics properties *Mehanička svojstva*	**Wood type** *Vrsta drva*	**Control** *Kontrolni uzorak*	**175 °C**	**205 °C**	**Change % in (Control / 175 °C)** *Postotna promjena (kontrola / 175 °C)*	**Change % in (175 °C / 205 °C)** *Postotna promjena (175 °C / 205 °C)*
Bending strength *čvrstoća na savijanje*	Cedar / *cedrovina*	32.52	24.85	23.69	-23.5	– 4.67
	Scotch pine / *borovina*	46.11	33.26	26.38	-27.8	-20.69
	Oak / *hrastovina*	69.14	50.87	33.72	-26,4	-33.71
	Chestnut / *kestenovina*	30.81	30.16	28.84	-2.1	– 4.38
Elastical modulus *modul elastičnosti*	Cedar / *cedrovina*	16050	12270	11700	-23.5	– 4.65
	Scotch pine / *borovina*	22760	16420	13020	-27.8	-20.71
	Oak / *hrastovina*	34130	25110	16650	-26.4	-33.69
	Chestnut / *kestenovina*	15210	14890	14230	-2,1	– 4.43
Compression strength *čvrstoća na tlak*	Cedar / *cedrovina*	46.58	44.22	44.14	-5.0	– 0.18
	Scotch pine / *borovina*	44.03	41.72	39.68	-5.2	– 4.89
	Oak / *hrastovina*	63.00	62.86	62.86	-0.2	0.00
	Chestnut / *kestenovina*	49.42	45.63	41.81	-7.6	– 8.37
Shock strength *čvrstoća na udarac*	Cedar / *cedrovina*	26.59	18.77	17.29	-29.4	– 7.88
	Scotch pine / *borovina*	42.87	35.16	31.47	-17.9	-10.49
	Oak / *hrastovina*	61.06	44.78	28.70	-26.6	-35.91
	Chestnut / *kestenovina*	44.41	38.78	36.28	-12.6	– 6.45
Column strength *čvrstoća na izvijanje*	Cedar / *cedrovina*	32.52	24.85	23.69	-23.5	– 4.67
	Scotch pine / *borovina*	46.11	33.26	26.38	-27.8	-20.69
	Oak / *hrastovina*	69.14	50.87	33.72	-26.4	-33.71
	Chestnut / *kestenovina*	30.81	30.16	28.84	-2.1	– 4.38
Hardness *tvrdoća*	Cedar / *cedrovina*	2.754	1.394	1.154	-52.2	-17.22
	Scotch pine / *borovina*	2.180	1.810	1.570	-16.9	-13.26
	Oak / *hrastovina*	3.616	2.462	1.342	-31.9	-45.49
	Chestnut / *kestenovina*	2.014	1.568	1.254	-22.1	-20.03

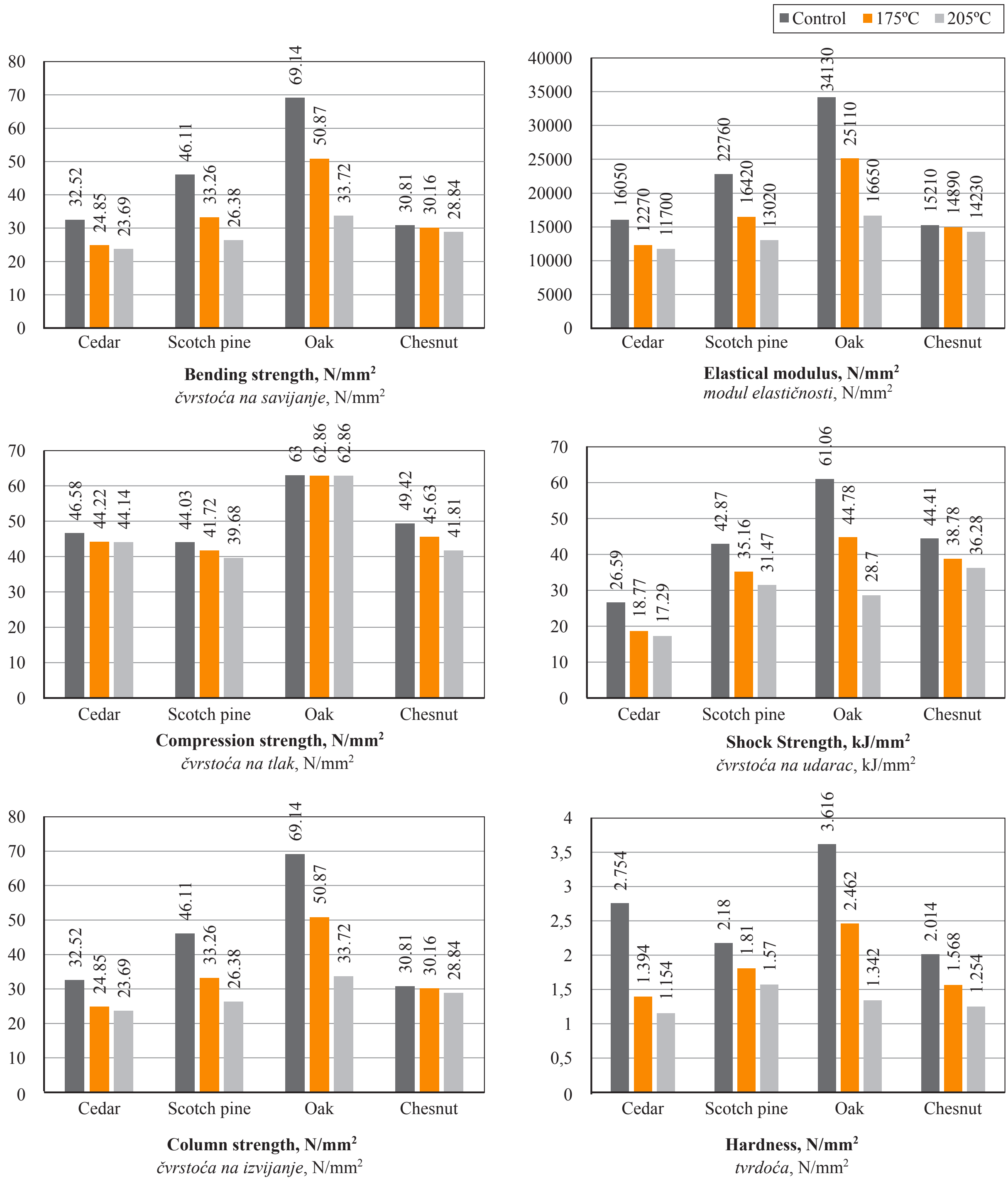

Figure 4 Changes in mechanical properties of wood species
Slika 4. Promjene mehaničkih svojstava drva

The averages for the change in hardness values, the averages for the interaction of wood and heat treatment in terms of the effect on hardness and the homogeneity groups of these averages are given in Table 13.

In terms of wood species in Table 13, the highest column strength was found in oak, followed by Scotch pine, cedar and chestnut samples, respectively. Compared to the hardness in the control samples, the hardness of each wood species decreased in the treated samples and the hardness decreased further as the heat treatment temperature increased.

It can be said that the decrease in hardness is due to the degradation of wood cell components (cellulose, lignin and hemicellulose) depending on the process temperature of heat treatment. These results are supported by the results of Gündüz *et al*. (2011) and Michiel *et al*. (2007). At the same time, in the dual interaction of these two factors, the highest hardness was found in oak control and oak – 175 °C samples. The lowest hardness was obtained in heat-treated cedar 205 °C samples. In the wood-treatment interaction, it can be said that the reason for the highest hardness in oak samples is that the cabin temperature of 175 °C is low for broadleaf oak and the heat treatment effect at this temperature is not sufficient for cellular degradation (cellulose and lignin). The low temperature (175 °C) created a pre-heat treatment causing a drying effect. In the heat treatment processes of 205 °C, it is seen that Scotch pine and cedar lost more resistance, and it can be said that this is due to the fact that coniferous samples undergo more degradation at high temperature causing more collapse in the cell walls. These results are supported by the results Türk *et al*. (2021), Zhou *et al*. (2024) and Adamcik *et al*. (2025).

4 CONCLUSIONS
4. ZAKLJUČAK

At the conclusion of this study, based on the changes in the mechanical properties of samples made from two different types of wood and subjected to heat treatment at two different oven temperatures, it was observed that at 175 °C heat treatment, there was a significant decrease (0.2-52.2 %) in the mechanical properties of all wood samples compared to the control samples (Table 14). At this temperature level, a significant thermal treatment effect occurred in all wood samples, reducing their mechanical properties by degrading the chemical properties of the wood species, despite their different structural properties.Changes in the mechanical properties of wood species are shown in Figure 4.

After applying heat treatment at 205 °C, the change values in the mechanical properties of the same wood types were compared with the heat treatment values at 175 °C. The change rates at the oven temperature level of 205 °C were quite low (0.18-4.67 %) for all mechanical properties of cedar and chestnut wood. Based on these results, it can be said that a heat treatment temperature level of 175 °C is sufficient for cedar and chestnut wood types, and that applying heat treatment at higher temperature levels would be unnecessary and wasteful of energy.

It was determined that the percentage change in mechanical resistance in yellow pine wood samples subjected to heat treatment at 175 °C decreased even further to between 10-20 % after heat treatment at 205 °C. This situation may be attributed to the prolonged dissolution and evaporation of resin and other extractive substances present in Scots pine at the initial temperature, causing a delay in the decomposition of wood components. It can be said that the full effect of heat treatment on Scots pine can be achieved by increasing the oven temperature by a few degrees (5-10).

However, in oak wood samples, it was determined that the changes in mechanical resistance after heat treatment at 175 °C continued to decrease further after heat treatment at 205 °C, with a decrease rate between 33.69 % and 45.45 %. In this case, it can be said that applying a heat treatment of 175 °C to oak wood is not sufficient for the heat treatment to be fully effective, and that an oven temperature of 205 °C would be more appropriate. The fact that the change in the compressive strength of oak wood was very low at both heat treatment levels could not be fully evaluated.

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