

## MECHANICAL PERFORMANCE OF HEAT-TREATED NORWAY SPRUCE (*PICEA ABIES*) WOOD

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**Abstract:** *In this study, the mechanical characteristics of Norway spruce wood (*Picea abies*) from Bosnia and Herzegovina were investigated by thermal treatment at three different temperatures (specifically, 180, 190, and 210°C) and treatment durations (namely, 2, 3, and 4 hours). For this purpose, the maximum 4-point bending force, the modulus of elasticity in bending, the compression strength parallel to the grain, and the compression strength perpendicular to the grain in treated and untreated specimens were evaluated. Results indicated that the relationship between temperature and duration modification affects the mechanical properties of wood specimens. The results revealed that the relationship between temperature and duration modification influenced the mechanical properties of the wood samples. Specifically, in terms of compression strength, it was observed that the heat-treated specimens exhibited improved mechanical properties compared to the unmodified specimens. However, for the maximum 4-point bending force and modulus of elasticity, the results indicated a decrease in mechanical properties.*

**Key words:** *wood, mechanical properties, thermal modification, spruce.*

### 1. Introduction

Wood is a highly significant building material, particularly Norway spruce wood, which holds great importance in Central Europe [3]. However, many European wood species have non-durable wood, limiting their use in outdoor applications. To overcome this limitation, protective measures are necessary to enhance the performance of wood in

moist conditions. In the past, biocidal preparations were commonly used to mitigate wood degradation [9]. Nowadays, non-biocidal solutions are preferred, and various biocide-free modifications are available on an industrial scale [10]. One well-established technique is thermal modification or heat treatment [11]. According to data from [13], Europe produces up to 530,000 m<sup>3</sup> of heat-treated (HT) wood annually. A study by

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[15, 19] examined the influence of different heat modification temperatures on the changes in wood's basic chemical components, color, physical characteristics, and mechanical properties. The primary drawbacks of wood, such as dimensional stability and biological durability, stem from the abundance of hydroxyl groups (OH) in its main polymers [16, 17]. Numerous research efforts focus on protecting wood without using toxic chemicals. Heat treatment offers a potential solution since it can upgrade species with lower durability or dimensional stability into entirely new products with superior properties [21, 22]. Heat-treated wood is a convenient and eco-friendly method that enhances durability and moisture performance [23, 24]. Gaff et al. [6] investigated the properties, durability, and mechanical characteristics of thermally modified and copper-impregnated laminated girders exposed to outdoor conditions. Experimental research conducted in [7, 8] examined the behavior of heat-treated Norway spruce (*Picea abies*) wood, with maximum bending and tensile strength being the output parameters of interest. According to Pelaez-Samaniego et al. [14], wood thermal treatment reduces the water absorption and thickness swelling of wood composites, which is mainly attributed to the removal of hemicelluloses. Hemicelluloses are the most thermally unstable components of wood, and their degradation leads to changes in the chemical composition and structure of wood. These changes affect the mechanical properties of wood in different ways, depending on the product and the conditions of the treatment. On the other hand, [2] reviewed the effects of

wood thermal treatment on decay resistance and found that heat-treated wood showed reduced mechanical properties compared to untreated wood. They attributed this to the loss of mass and strength due to thermal degradation, as well as to the formation of cracks and fissures in the cell wall structure. The authors also noted that the mechanical properties of heat-treated wood depended on the species, initial moisture content, heating medium, temperature, duration, and cooling rate. Čabalová et al. [1] studied the effect of thermal treatment on pedunculate oak (*Quercus robur* L.) wood. They found that the physical and mechanical properties of oak wood, such as density, equilibrium moisture content, color lightness, and yellowness, decreased as the temperature increased. The compression strength and redness varied during thermal treatment, and reached maximum values during the treatment at 180°C. Norway spruce was chosen as the wood species for this study because it is one of the most important and widely distributed coniferous species in Europe, especially in Central Europe. It is also a major source of timber and pulpwood, and has various applications in construction, furniture, musical instruments, and bioenergy. However, Norway spruce wood has low natural durability and dimensional stability, which limits its use in outdoor conditions. Improving the performance and extending the service life of Norway spruce wood is a relevant and significant research topic. Therefore, the aim of this paper was to investigate the mechanical characteristics of Norway spruce wood (*Picea abies*) from Bosnia and Herzegovina through thermal treatment at different temperatures and durations. The specific objectives were to

evaluate the maximum 4-point bending force, the modulus of elasticity in bending, the compression strength parallel to the grain, and the compression strength perpendicular to the grain in both treated and untreated specimens.

## 2. Materials and Methods

### 2.1. Material

The study utilized Norway spruce (*Picea abies*) specimens obtained from the Uno-San canton in the west of Bosnia and Herzegovina. To achieve an equilibrium moisture content (EMC) of 12%, all specimens were air-conditioned under standardized conditions, maintaining a relative humidity (RH) of  $65\% \pm 3\%$  and a temperature of  $20 \pm 2^\circ\text{C}$ . As part of this study, a group of 20 samples was formed, including unmodified wood (CS) and thermally modified wood (TMS). This group of materials was selected with the aim of investigating and comparing the characteristics between these two types of wood. The samples of unmodified wood served as a basis for comparison and reference, while the samples of thermally modified wood were included to study the changes in the physical and chemical properties that occur during thermal treatment. This selection of samples enables a deeper understanding of the differences between unmodified and thermally modified wood, providing valuable insights for application in various industrial and construction projects. The unmodified samples exhibited an average density of  $0.366 \text{ g/cm}^3$ , whereas the modified samples had an average density of  $0.353 \text{ g/cm}^3$ . Additionally, the average moisture content of the samples ranged from 8 to 12%.

### 2.2. Thermal Treatment (TM)

All samples were appropriately labeled based on the experimental design and then subjected to oven drying for a duration of 24 hours at a temperature of  $103^\circ\text{C}$ , before undergoing thermal modification. Once the drying process was completed, the samples were cooled within a desiccator and their respective masses were determined. These measured masses served as the basis for calculating the mass losses attributed to thermal modification (TM). For thermal treatment (TM), the wood samples underwent a commercial process called Silvapro<sup>®</sup>, conducted by Silvaproduct in Ljubljana, Slovenia [18]. The TM process involved an initial vacuum and heating of the Norway spruce samples to maximum temperatures ranging from  $180^\circ\text{C}$  to  $210^\circ\text{C}$ . Different durations of the TM process were applied at intervals of 2, 3, and 4 hours. Silvapro<sup>®</sup> wood is treated using superheated steam within a controlled atmosphere of high pressure, ensuring that the desired temperature and moisture levels are achieved. Once the optimal conditions are reached, the wood is held in place for a specific duration to ensure effective thermal modification. Following the treatment, a crucial cooling phase begins, which plays a vital role in attaining the desired properties of the wood. The wood is gradually cooled under controlled conditions until it reaches room temperature. This cooling process is carefully managed to ensure that the ambient temperature remains below  $30^\circ\text{C}$  for 24 hours, thereby guaranteeing the effectiveness of the thermal modification process.

### 2.3. Mechanical Tests Performed

#### 2.3.1. Determination of Maximum Compressive Strength (MCS)

Small clear samples were obtained for testing various properties: compression strength parallel to the grain, compression strength perpendicular to the grain  $9 \times 4.5 \times 7.0$  (cm), bending strength  $2.0 \times 5.0 \times 38.0$  (cm), and modulus of elasticity in bending  $2.0 \times 5.0 \times 38.0$  (cm). To determine the maximum compressive strength (MCS), 20 defect-free samples with dimensions of  $9 \times 4.5 \times 7.0$  (cm) ( $h \times b \times l$ ) were prepared. The ZWICK/ROELL Z600 Universal Testing Machine was employed for the test, applying a load at a rate of 600 N. The obtained values were then used to calculate the compressive strength using equation (3).

$$\sigma = \frac{F_{\max}}{b \cdot l} \quad (1)$$

where:

- $\sigma$  is the maximum Compressive Strength [N/mm<sup>2</sup>];
- $b$  – the width [mm];
- $d$  – the depth [mm];
- $F^{\max}$  – the load [N].

#### 2.3.2. Assessment of Bending Strength

The SIL-50KNAG testing machine, manufactured by SHIMADZU, was used in the experiments. This machine features a working cylinder positioned at the top, while the lower head remains stationary. The bending action occurs as the working cylinder moves downward. To measure the bending, four points are monitored, allowing for the determination of force values from the diagram. The testing procedure in this study adhered to the

guidelines specified in standard EN 408 [4]. The dimensions of the specimens were: bending strength ( $2.0 \times 5.0 \times 38.0$  cm), ( $h \times b \times l$ ) and modulus of elasticity in bending ( $2.0 \times 5.0 \times 38.0$  cm). The test specimens, which had a minimum length of around 19 times the section's height, were subjected to symmetrical bending loads at two points over a span approximately 18 times the height.

### 2.4. Statistical Analysis

A statistical analysis was conducted using Microsoft Excel in conjunction with the Analyse-it for Microsoft Excel 4.90 software (developed by Analyse-it Software, Ltd., located in Leeds, United Kingdom). The data obtained from the thermal Norway spruce samples were compared to the control samples, and the statistical significance of any differences were determined using the Student's *t*-test. A *p*-value of 0.005 was used as the threshold for statistical significance in this analysis.

### 3. Results and Discussion

The relationship between force and deformation parallel and perpendicular to the direction of the fibers as a result of the compression is illustrated in Figure 1. The curves displayed on the graph represent the impact of modification temperature on the compression strength.

The highest compressive force was observed in the samples that were tested perpendicular to the parallel to the grain that were heat-treated at a temperature of 210°C. The highest force was recorded in the samples that were tested perpendicular to the grain at a temperature of 195°C for 3 h (Table 1).

Influence of modification temperature and modification duration on average values of mechanical properties of thermally modified spruce wood.

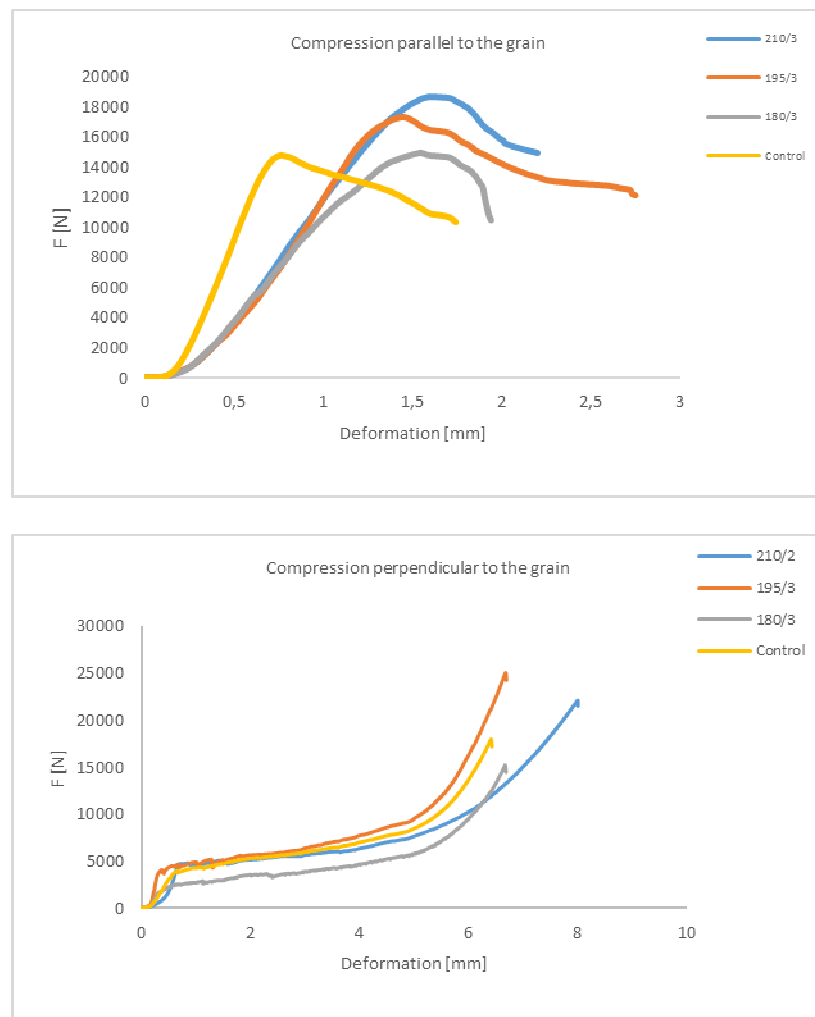


Fig. 1. Relation between force and deformation during compression tests parallel (the first figure) and perpendicular to the grain (the second figure) determined in samples modified at different temperatures

The differences in compressive strength resulting from the use of different temperatures in the thermal modification process are evident from the results of the compression test, as depicted in Table 1. Notably, the highest compressive force was observed in the samples subjected to

heat treatment at a temperature of 210°C. For a duration of 4 hours at 210°C, the maximum compressive strength increased by 25% compared to the unmodified wood. Similarly, at a temperature of 195°C, significant enhancements in compressive strength were observed

across different durations. Specifically, for the samples treated at 195°C, the maximum compressive strength increased by 15% for a duration of 2 hours, by 20% for 3 hours, and by 10% for 4 hours, all relative to the unmodified wood. On the other hand, the samples treated at 180°C showed a more modest increase of 1% in maximum compressive strength. Further

analysis reveals that there is an overall trend of increasing compressive strength as the temperature of thermal modification rises. This indicates that higher temperatures, such as 210°C and 195°C, have a positive impact on the wood's ability to withstand compressive forces.

Table 1

*Influence of temperature modification and duration modification on the average values of the mechanical properties of thermally modified spruce wood*

Modified temperature [°C]	Modified time [h]	B [kN]	SD	MOE [N/mm <sup>2</sup> ]	C <sub>⊥</sub> [N/mm <sup>2</sup> ]	SD	C <sub>  </sub> [N/mm <sup>2</sup> ]	SD
Spruce Control (CS)	-	3.44	0.58	12971	12.15	2.07	40.19	1.24
(TMS) 180	2	2.54	0.95	10050	15.44	1.34	43.33	1.01
	3	2.01	0.86	9821	13.03	1.22	42.20	1.53
	4	2.62	0.72	11321	13.74	1.24	39.86	0.91
(TSM) 195	2	2.31	0.97	10640	16.03	1.72	46.24	0.98
	3	3.15	1.13	12600	14.90	1.31	48.11	1.20
	4	2.51	1.02	11011	12.51	1.23	47.81	1.05
(TMS) 210	2	2.98	1.10	10794	17.02	1.30	50.54	0.93
	3	2.48	0.98	9834	15.38	1.65	51.06	1.15
	4	2.26	1.21	9032	14.64	1.72	53.49	1.25

B - Bending force of four points, MOE – Modulus of elasticity, C- Compression, SD - St. Deviation

The increase in the compressive strength of the wood samples treated at higher temperatures can be explained by the chemical changes that occur during thermal treatment. According to Fajdiga et al. [5] thermal treatment causes the degradation of hemicelluloses, which are the most thermally unstable components of wood. Hemicelluloses are also responsible for the formation of hydroxyl groups (OH) in wood, which make it more hygroscopic and prone to swelling and

shrinking. As a result of reducing the amount of hemicelluloses and hydroxyl groups, thermal treatment improves the dimensional stability and moisture resistance of wood, which in turn enhances its mechanical strength. Another possible mechanism is the formation of cross-linking bonds between the remaining wood components, such as cellulose and lignin, during thermal treatment. These bonds can increase the stiffness and rigidity of the wood cell wall,

making it more resistant to deformation and fracture. This is supported by Li et al. [12], who found that thermal treatment promoted a chemical reaction between phenol–formaldehyde resin and wood, resulting in improved compressive stress. The results are in line with some previous studies that also reported an increase in the compressive strength of wood parallel to the grain after thermal treatment. For example, Roszyk et al. [20] found that thermally treated beech wood had higher compressive strength than untreated wood at different moisture levels. However, our study also contradicts some other studies that reported a decrease in the compressive strength of wood perpendicular to the grain after thermal treatment. For example, Li et al. [12] found that thermally treated spruce wood had lower compressive strength than untreated wood when the growth ring orientation was 40 degrees. This discrepancy may be due to the different wood species, growth ring orientations, thermal treatment conditions, and testing methods used in different studies. The heat-treated spruce wood samples also exhibited higher maximum force values during testing (as shown in Figure 1), further supporting the influence of temperature on compressive strength. These findings highlight the importance of considering both temperature and duration during the thermal modification process to achieve the desired enhancements in compressive strength. The results demonstrate that using higher temperatures, such as 210°C and 195°C, for appropriate durations can significantly improve the compressive strength of spruce wood. Meanwhile, lower temperatures, such as 180°C, have a more limited effect on enhancing compressive

strength. These insights provide valuable guidance for optimizing the thermal modification process, enabling the selection of appropriate temperature and duration parameters to achieve the desired mechanical properties for various applications. As can be seen from the results in Table 1, the relationship between maximum bending force (B) in unmodified wood and the measurement of maximum force in the modified tests is different for each specific temperature and duration of the thermal modification process. Notably, the maximum force values remained consistent in the wood treated at 195°C for a duration of 3 hours. The results indicate a percentage reduction in maximum bending force (B) and MOE in the spruce wood samples, ranging from 20% to 50%, depending on the specific temperature and duration of the treatment. For instance, at a temperature of 180°C, the maximum bending force and MOE values were slightly reduced compared to the unmodified wood. However, at a temperature of 195°C, the maximum bending force and MOE exhibited variations depending on the duration of treatment. In particular, for a duration of 3 hours, there was a notable increase in the maximum bending force and MOE. Similarly, at a temperature of 210°C, the maximum bending force and MOE also varied with the duration of treatment. These findings highlight the influence of both temperature and duration on the mechanical properties of the spruce wood samples. The thermal modification process can lead to changes in the wood's cell wall structure, which in turn affect its bending strength and elasticity. While there may be a reduction in maximum bending force and MOE, it is crucial to

consider the overall trade-off between the enhanced properties and the desired mechanical characteristics for specific applications. By carefully selecting the appropriate temperature and duration parameters during the thermal modification process, it is possible to optimize the spruce wood's mechanical properties, ensuring they align with the intended application requirements.

#### 4. Conclusions

The study investigated the effects of thermal modification on the mechanical properties of spruce wood. The compressive strength properties of thermally modified wood were found to be comparable to those of the reference wood at 2 hours and 180°C. However, increasing the temperature and duration of treatment resulted in a significant decrease in the fracture force of the treated samples during the bending tests. Both bending force and Modulus of Elasticity (MOE) decreased in the treated samples compared to the control samples, with a more prominent reduction observed in the samples treated for 4 hours. These findings suggest that thermal modification affects the bending properties and elasticity of spruce wood, making it less able to withstand bending forces and reducing its overall flexibility. This information is important for determining the suitability of thermally modified wood for applications where strict mechanical performance requirements are not essential, such as paneling, decorative purposes, or non-structural elements. It is crucial to use appropriate time and temperature parameters during the heat treatment process to minimize any potential loss in

strength values. However, further evaluation of dimensional stability is recommended before considering heat-treated wood for applications that specifically require dimensional stability.

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