forests

MDPI

Article

Bending Properties of Pleated Wood Thermally Treated at 160 °C and 200 °C Temperatures

Mátyás Báder , Bíbor Júlia Horváth and Miklós Bak *

Faculty of Wood Engineering and Creative Industries, University of Sopron, Bajcsy-Zsilinszky 4, 9400 Sopron, Hungary; bader.matyas@uni-sopron.hu (M.B.)
* Correspondence: bak.miklos@uni-sopron.hu

Abstract

This study investigates the combined effects of compression along the grain by 20% after steaming (pleating), and thermal treatment on the mechanical and physical properties of beech (*Fagus sylvatica* L.) and sessile oak (*Quercus petraea* (Matt.) Liebl.). Pleating significantly increased plasticity and maximum deflection, reaching 339% of untreated values in beech and 337% in oak. However, it reduced bending strength and modulus of elasticity to about 50%. Keeping the specimen compressed for 5 h (fixation) during the thermo-hydro-mechanical modification process of pleating further decreased the modulus of elasticity to 26%–29% of untreated levels. Thermal treatment at 160 °C increased bending strength of fixated specimens to 120.5% in beech and 125.3% in oak, partially restoring strength, while at 200 °C, it decreased drastically to 26.7% and 21.5%, respectively. Density was reduced by thermal treatment, with oven-dry values decreasing by 6.2% (beech) and 12.7% (oak) at 160 °C, and by 18.2% and 25.1% at 200 °C. The results indicate that high-temperature treatment (200 °C) leads to wood with brittle properties.

Keywords: combined wood modification; thermal modification; thermo-hydromechanical modification; compression parallel to grain; *MoE*; *MoR*; density

check for updates

Academic Editor: Marco Fioravanti

Received: 26 September 2025
Revised: 29 October 2025
Accepted: 5 November 2025
Published: 7 November 2025

Citation: Báder, M.; Horváth, B.J.; Bak, M. Bending Properties of Pleated Wood Thermally Treated at 160 °C and 200 °C Temperatures. *Forests* **2025**, *16*, 1702. https://doi.org/10.3390/f16111702

1. Introduction

Pleating is a thermo-hydro-mechanical modification process that involves the compression of wood along the fibers under hot, steam-saturated conditions [1]. The process results in wood that is easily bendable in both hot and cold conditions compared to untreated wood [1]. A compression ratio of 20% is recommended to be performed in green condition to ensure the same initial conditions. The compressed wood will spring back when the compressive force is removed, and will suffer a residual shrinkage of 3%–10%. Pleated wood differs from untreated timber in that it can be bent with a much lower force to failure to a greater extent, and can be finished under cold conditions. It is mainly used in the furniture industry and can be machined in the same way as its untreated counterparts [2]. There are several pleating methods, so the chosen method should be adapted to the necessary properties of the product. The compression ratio is the primary factor affecting the subsequent properties, typically 20% of the original length. The time to hold the wood in a compressed state (fixation) also plays a significant role [3].

As the cell walls are damaged during compression, it is clear that the material will be able to withstand less force after treatment, and at the same time, it will be less resistant to the change in shape because of the changed circumstances. As the degree of compression or the duration of fixation increases, the ratio of change in strength values also increases. The bending modulus of elasticity (*MoE*) for beech decreases to about 30% of that of untreated wood at a 15% compression ratio, and to about 25% at a 20% compression ratio. The trend is similar for oak samples, where it is almost halved at a 10% compression ratio, and slightly further reduced at a 20% compression ratio [4]. Bending strength (*MoR*) values also decrease with modification, almost halving at 20% compression for beech and about 60% for oak, also at a 20% compression ratio [5,6]. Pleating has a negligible effect on compressive strength but halves the compression modulus of elasticity [3]. The longitudinal shrinking and swelling of wood compressed along the grain is about 6 times higher than that of untreated wood, so further research is warranted to mitigate this. One such option is the thermal treatment of pleated wood, whose effects on mechanical properties (bending test and density test) are shown in this study.

The result of thermal treatment is influenced by a number of factors: the anatomical structure of the wood (wood species), extractives, moisture content, environmental factors such as pressure, moisture present in the environment during thermal treatment, oxidative or inert atmosphere, and the duration and intensity of the thermal treatment. The inert atmosphere favors thermal decomposition processes, while the presence of oxygen favors oxidative decomposition processes, especially at higher temperatures [7]. Furthermore, extractives, which are present in small quantities in wood compared to other constituents, play an important role. Their presence may inhibit or facilitate certain transformations and decomposition processes. The transformation threshold temperature can also be slightly influenced by the rate of temperature change in variable temperature treatments [7]. In many cases, longer thermal treatments can achieve the same results as shorter but higher temperature treatments that are more intensive.

The study by Borůvka et al. [8] investigates the impact of thermal treatment on the mechanical properties of beech wood. Results indicate that thermal treatment conducted at 165 °C and 210 °C reduces mechanical properties such as the dynamic and static elasticity modulus, *MoR*, impact toughness, and hardness. The decline in these properties is attributed to changes in the chemical composition of wood due to high temperatures, i.e., the degradation of hemicelluloses and the alteration of lignin structures. Thanks also to these changes, thermal treatment changes the color of the wood, making it darker. The wood becomes biologically more durable. This treatment enhances the dimensional stability of wood and reduces its hygroscopicity, making it more suitable for applications requiring stable wood dimensions.

Thermal treatment at 200 °C for 24 h resulted in an 8% reduction in the oven-dry density of beech wood in the study by Sinkovic et al. [9], while only 1.5% reduction was found for oak wood.

Borůvka et al. [8] reported that thermal treatment at 165 °C reduced *MoR* by approximately 15% compared to untreated beech wood, while at 210 °C, the reduction was about 30%. A significant relationship was found between hemicellulose and *MoR* by Gaff et al. [10]. Similar trends are observed in oak after a 10 h treatment, with *MoR* decreasing by around 20% at 150 °C, as noted by Korkut et al. [11]. The structural integrity of lignocellulose is compromised at higher temperatures [10].

The *MoE* of beech wood increased by approximately 9% after a short treatment at 160 °C and decreased up to 13% at 210 °C, as shown by Gaff et al. [12]. This reduction is linked to the loss of stiffness due to polymer breakdown. Yilmaz Aydin and Aydin [13] found similar trends, a 3% increase at 150 °C and a 21% decrease at 210 °C for oak. Oak retains slightly lower stiffness compared to beech at lower treatment temperatures.

The thermal treatment of wood, particularly species like diffuse-porous beech (*Fagus sylvatica*) and ring-porous oak (*Quercus* spp.), is a process used to improve wood properties such as dimensional stability and resistance to biological degradation. There are still a lot of gaps in research, such as the need for studies focused on the long-term durability and performance of thermally treated beech and oak under various environmental conditions. Higher-density hardwood species are also suitable for pleating, which makes the wood pliable through compression along the grain after softening the fibers with steam. Unfortunately, pleated wood reacts to moisture changes with much greater dimensional and shape changes than untreated wood. The combination of the two major modification processes introduced may result in wood with unique mechanical properties. This is a systematic study that partially fills the scientific gaps in this field, as there are no papers in the literature from the last 100 years dealing with the combination of the mentioned two wood modifications. Thus, the specific novelty of this work is that this study focuses on five types of bending properties and density after pleating by 20%, followed by thermal treatment at temperatures of 160 and 200 °C. This study may help to initiate the possible future use of such a combined modification and to broaden its potential uses, thereby increasing the range of applications for environmentally friendly modified wood. Pleated wood is primarily used in the furniture industry and interior design to produce curved parts such as for benches, chairs, jewelry, shoe insoles, wall covering, etc. [14]. With proper post-treatment, like thermal treatment, it may be used as parts of interior and furniture in kitchens, bathrooms, terraces, yacht interiors, etc., but its structural application remains limited due to restrictions by standards used in the construction industry.

2. Materials and Methods

Beech (*Fagus sylvatica* L.) and sessile oak (*Quercus petraea* (Matt.) Liebl.) wood were used in the measurements. Beech is more important in industrial applications in terms of compression and steam bending, while oak can be used as a representative for the compression and thermal treatment of ring-porous wood species. For the tests, we created an untreated and several treated samples for both species. Since wood is inhomogeneous and anisotropic, and the mechanical and chemical properties can vary greatly even within a single species, we used specimens from the same section of a log for both species. Only suitable, defect-free materials with no or only light slope of grain was used for compression, as described in the study of Báder [2]. The initial dimensions of the specimens were 20 × 30 × 200 mm (T × R × L). The wood was plasticized by steaming for a minimum of 45 min at atmospheric pressure in saturated steam at 100 °C, based on the size of the specimens [15]. Specimens were compressed along the grain by 20% (pleated) with the technology described in the article of Báder and Németh [3]. One half of the compressed specimens were fixated (kept compressed) for a short time (one minute), while the compressed-fixated samples were fixated for significantly longer (five hours). Fixation longer than 5 h causes very little change over time, which is why this period was chosen. However, because specimen production is still very slow even with the 5 h long fixation, only three specimens were produced for all fixated samples, as shown in Table 1, and at least ten for all other samples. It should be noted that the trends are still clear and consistent in terms of the permanent change in length of the specimens after treatment, which is in line with the bending properties based on a previous study [14]. In other words, the expected results and conclusions of the research are adequately supported by these specimen numbers. It should also be noted that these sample sizes doubled for the bending tests, because two bending specimens were prepared from each initial specimen.

Thermal modifications were carried out in the range between 150–160 °C and 240–250 °C [16,17]. In this study, one of the temperatures used was 160 °C, close to the lower limit, while the higher temperature was 200 °C, which is used in many industrial solutions. Thermal treatment was carried out under normal atmospheric conditions, in an oxidative atmosphere. The first step was drying the samples at 103 °C after conditioning. The samples were thermally treated in a custom-made vacuum-pressure chamber. The chamber is pressure-resistant and can be used to create both vacuum and overpressure. The chamber wall is insulated, and electric heating elements at the bottom ensure the required temperature during treatment. The temperature is controlled by a PLC (programmable logic controller; a computer used to automate electromechanical processes) system. Thermal treatment was carried out with the following parameters: heating to 40 °C, then reaching the tempering temperature (100 °C) at a rate of 10 min/°C. The heat retention was only 2 h, as the samples had already been dried at 103 °C beforehand. This was followed by thermal treatment for 10 h. The increase in the temperature was also 10 min/°C. The final temperature was 160 or 200 °C, depending on the sample. The cooling rate was 4 min/°C (Figure 1), followed by conditioning under normal conditions again (20 °C and 65% relative humidity).

Table 1. Specimen number in each sample of the test.

		Thermally Not Treated	Thermally Treated at 160 °C	Thermally Treated at 200 °C
Beech	Uncompressed	12	10	10
	Pleated	10	10	10
	Fixated	3	3	3
Oak	Uncompressed	16	10	16
	Pleated	10	10	10
	Fixated	3	3	3

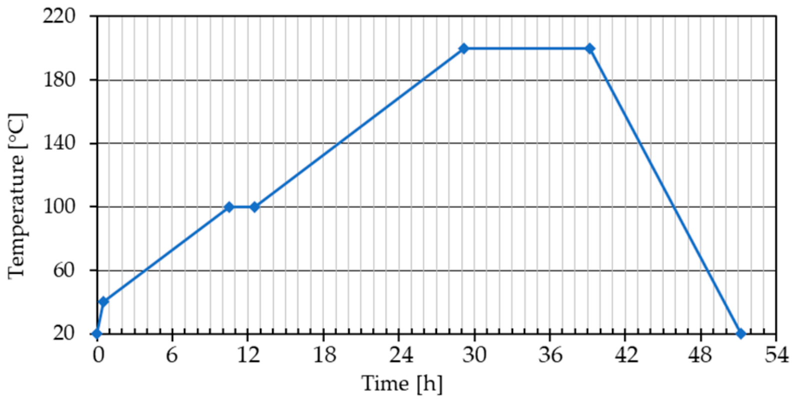

Figure 1. Parameters for thermal treatment at 200 °C.

Bending test specimens with a cross-section of 19 × 11 mm were prepared from the finished samples, thus doubling the amount of material that could be tested. Their length was 162–200 mm, depending on the type of treatment, which was more than sufficient for the 140 mm support span. The distance between the upper rollers was set to 50 mm. The specimens were tested flatwise as this is the typical use of pleated wood during its bending. Both pleating and 4-point bending tests were performed using an Instron 4208 (Illinois Tool Works Inc., Norwood, MA, USA) universal material testing machine. Several properties of the test specimens changed significantly, so the ideal test rate is different for each sample. Taking into account the requirements of ISO 13061-03 [18], the failure time should be between 0.5 and 5 min. For untreated samples, the rate was 8 mm/min; for both compressed and fixated samples, it was 16 mm/min, while for samples thermal-treated at 160 °C, the rate was 4 mm/min. For samples thermally treated at 200 °C, the rate was 2 mm/min, with the exception of beech samples thermal treated at 200 °C, where the bending test had to be performed at a rate of 4 mm/min. The calculations related to bending tests were performed based on Báder and Németh [3].

3. Results and Discussion

3.1. Density

Density, similarly to moisture content, affects the strength of wood, and in many cases, it can also indicate the degree of degradation caused by various treatments. For this reason, it is important to know its exact value. Since moisture content significantly affects density, it is worth dealing with oven-dry values when analyzing the results of the tests. However, densities of samples conditioned under normal conditions are also presented, as this provides a realistic view for the utilization of wood (Table 2). Pleating (compression along the grain after steaming) increases oven-dry density by 3.2% and fixation (keeping the pleated specimen compressed) increases it by 6.3% for beech. These are −7.8% and 1.8% for oak, respectively. The negative value indicates a decrease in oak density due to pleating, which is caused by its significant spring-back. In contrast, thermal treatment causes significant differences, which is in agreement with the literature [19–21]. At 160 °C, there is a 6.2% decrease, while at 200 °C, there is an 18.2% decrease for beech. For oak, these are 12.7% and 25.1%, respectively. These can be attributed to the chemical changes and degradations that were much stronger due to the thermal treatment at 200 °C [10,16,22]. Compression significantly reduces the density-reducing decomposition effects of thermal treatment. This may be because the altered wood structure makes it more difficult for certain components to evaporate. In addition, not only the buckled cell walls but also the steaming prior to compression may have limited the decomposition, as the tissue elements and their components interact differently during thermal treatment [14,23]. The analysis also revealed some positive values; for example, thermal treatment at 200 °C temperature increased the density of pleated oak wood by 3.8%. The variance of the density of the pleated sample is 6.7%, and that of the pleated and thermally treated sample is 4.7%—both are higher than the difference between their averages. Such a small difference between the averages (3.8%) is probably due to the inhomogeneity and variability of wood itself; however, earlier studies also reported increased density as a result of thermal modification [24]. Comparing the results for the two wood species, it is clear that despite the higher untreated density of oak, in many cases, it became less dense than beech as a result of the treatments. The higher extractive content explains the greater weight loss that may have occurred during both the steaming prior to compression and the thermal modifications. The greater decrease in oak density is mostly due to its significantly higher extractive content compared to beech wood. Significantly more extractives were removed, while the decrease in extractive content did not affect the volume of oak wood.

Table 2. Average densities [kg/m^3] conditioned to constant weight, moisture contents (MCs) refer to the conditioned state. The standard deviations are shown after the ± sign. Conditioning was performed at a temperature of 20 °C and a relative humidity of 65%.

	Beech			Oak		
	Conditioned Density	MC	Oven-Dry Density	Conditioned Density	MC	Oven-Dry Density
Untreated	720 ± 26	11.9%	694 ± 27	761 ± 25	12.3%	726 ± 25
Thermally treated at 160 °C	671 ± 20	7.4%	651 ± 20	656 ± 25	7.6%	634 ± 26
Thermally treated at 200 °C	580 ± 16	4.4%	568 ± 16	557 ± 31	4.4%	544 ± 31
Pleated	735 ± 32	11.4%	716 ± 33	714 ± 48	13.1%	670 ± 48
Pleated and thermally treated at 160 °C	712 ± 33	7.7%	692 ± 34	657 ± 41	7.5%	631 ± 37
Pleated and thermally treated at 200 °C	672 ± 15	4.3%	661 ± 15	710 ± 34	4.4%	695 ± 33
Fixated	749 ± 54	11.5%	738 ± 50	766 ± 43	13.5%	740 ± 42
Fixated and thermally treated at 160 °C	723 ± 31	7.5%	710 ± 31	788 ± 22	7.9%	769 ± 24
Fixated and thermally treated at 200 °C	701 ± 39	4.4%	694 ± 40	707 ± 29	4.6%	693 ± 29

Thermal treatment at 160 °C decreased MC to approximately two-thirds (decrease between 32.9% and 42.3%, depending on the sample), while thermal treatment at 200 °C reduced MC to one-third in all cases (decrease between 61.5% and 66.3%, depending on the sample). This is expected to have a positive effect in terms of dimensional stability; however, it was not the focus of this study. Consequently, since pleated wood is very sensitive to moisture changes (it reacts with significant deformation), thermal treatment represents a significant advance in this area, without the use of chemicals and non-natural materials.

3.2. Bending Test

3.2.1. Bending Strength

Some of the most important but complex material characteristics can be determined by the bending test of wood [25,26]. These characteristics are specific to each wood species, but their values can be significantly influenced by factors such as the growth characteristics of the wood, the growing site, the moisture content of the tested wood, and the wood modification processes, among others. The strength of wood determines and limits its usability. Since the purpose of pleating is to make the wood easier to bend, this wood modification significantly affects the strength of the wood. Thermal treatment changes the chemical composition of the wood depending on its intensity, which also has a major impact on the properties of the wood. The combined use of the two treatments may cause significant changes in the strength values and other wood properties.

During the bending test, the material testing machine records time, force, and crosshead displacement every 50 milliseconds. Figure 2 shows graphs created using crosshead displacement and force data. These graphs clearly illustrate the difference of how the wood types changed based on the individual modifications as well as the combined modifications. They also enable the comparison of the reactions of the two main representatives, beech and oak of the two large deciduous wood species groups (diffuse-porous and ring-porous), to the treatments.

While untreated wood exhibits normal fracture characteristics typical for wood (Figures 2 and 3), thermal treatment shifts these properties toward brittleness. This is a well-known phenomenon that has been described in numerous publications [16,27,28]. Earlier studies reported that with a decrease in lignin content or the conversion of lignin, the reactivity of cellulose increases. Large cellulose fractions begin to cleave at temperatures above 180 °C. Treatment at 210 °C increases the proportion of low-molecular-weight cellulose fractions; the degree of polymerization decreases by 20% compared to untreated samples. The decomposition of crystalline cellulose begins at 260 °C, making it much more stable than amorphous hemicelluloses [29,30]. This causes brittleness and brittle fracture in thermally modified wood. The difference is more pronounced with more intensive thermal treatment. This also affects *MoR* and deflection, because wood can withstand less stress with less deflection due to the increased degradation of plastic components, hemicelluloses, and lignin. In contrast, compression along the grain (pleating) makes the graph, as well as the wood itself, distinctly plastic. This is primarily due to changes in the cell walls, which become buckled, allowing the wood to stretch more easily along the outer curve when bent [3,14,31]. In addition, the microfibrils that make up the cell walls also shift in position and become wavy, making the components of the cell walls more plastic [3]. Thermal treatment at 160 °C moderates the changes resulted by compression treatment, but pleated beech wood and especially fixated (pleated, then kept compressed for 5 h) beech wood remain more plastic than untreated wood. An earlier study showed that by increasing fixation time, the bendability of wood increases and the required bending force decreases proportionally. The peaky graphs of the untreated specimens gradually become rounded both by compression and increasing fixation time. Finally, specimens fixated for a long time become ductile and can undergo significant plastic deformation before fracturing [14]. For oak, only fixated wood remains much more plastic after a 160 °C thermal treatment. This difference between the two wood species is due to the structure of oak, which is loosened by large vessel rings in the earlywood, while beech is much more homogeneous.

Ring-porous cell structure, damaged by compression, breaks apart more easily. As a result of thermal treatment, the structure damaged by compression loses some of its plasticity and become more rigid, facilitating brittle fractures. However, thermal modification at 200 °C makes all compressed wood extremely brittle and low in resistance in terms of both strength and flexibility. At this point, thermal treatment alters the cell walls, and the cell-connecting elements are damaged by compression, mainly hemicelluloses. Chain mobility of hemicelluloses decreases, so plasticity is highly reduced [10,16,22]. Cell wall polymers, mainly hemicelluloses, largely lose their function and are unable to connect the microfibrils that provide stiffness and reinforcement along the grain, resulting in a mostly transverse-direction brittle fracture of both wood species. There are minor differences between the fracture patterns of beech and oak wood, but based on the evaluation of the bending test results, it can be stated that these differences are insignificant.

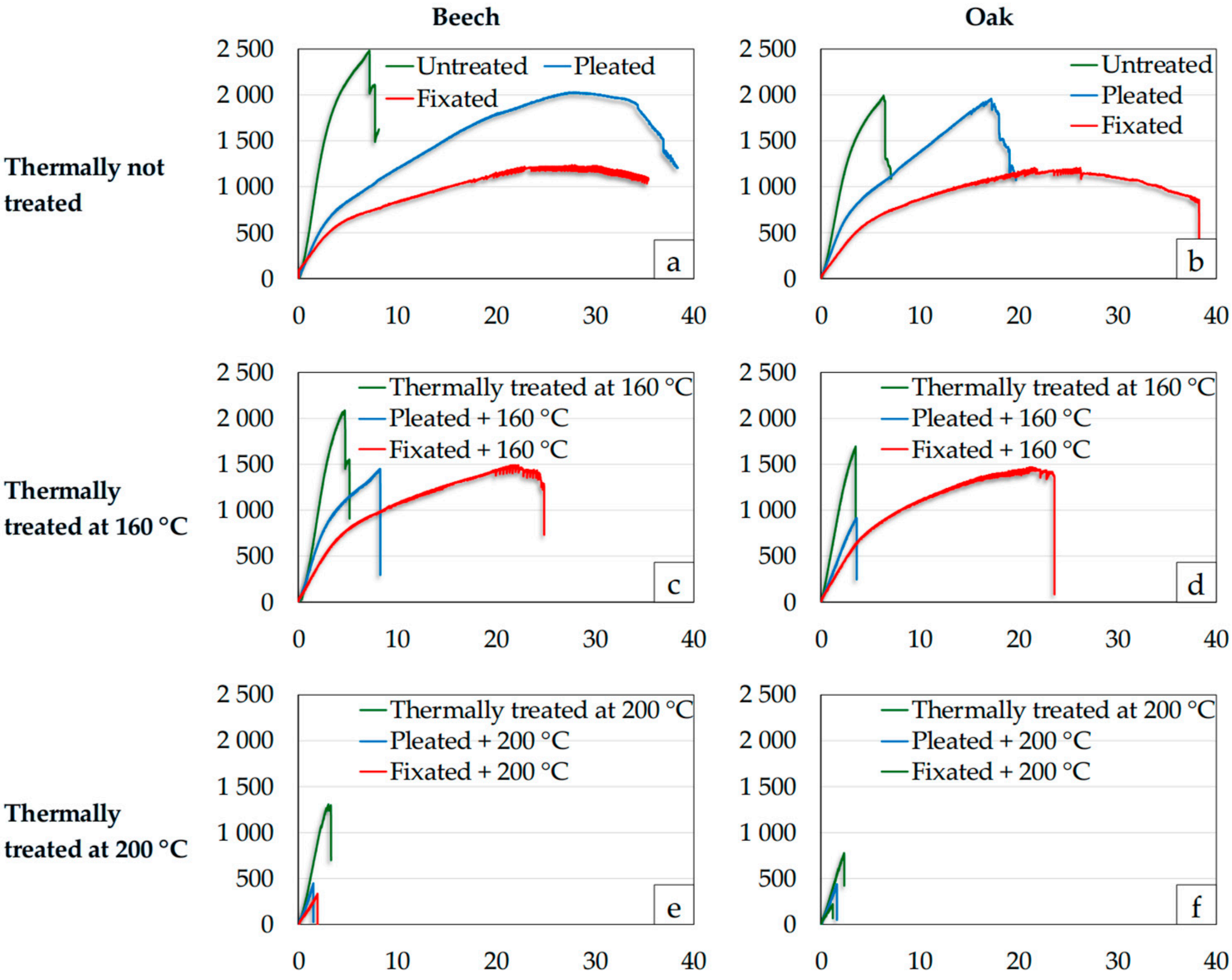

Figure 2. Graphs showing typical crosshead displacement (horizontal axis [mm]) versus force (vertical axis [N]) for all samples from the 4-point bending test. In fixated and some pleated specimens, the thickening of the curves occurs due to the slip of the specimens during bending, which is caused by the large deflection. All graphs show typical curves for uncompressed, pleated, and fixated specimens in case of (**a**) beech thermally not treated; (**b**) oak thermally not treated; (**c**) beech thermally treated at 160 °C; (**d**) oak thermally treated at 160 °C; (**e**) beech thermally treated at 200 °C; and (**f**) oak thermally treated at 200 °C. Abbreviations: Pleated—steamed and compressed along the grain by 20%; Fixated—pleated, then kept compressed for 5 h; Pleated + 160 °C—pleated and thermally treated at 160 °C; Pleated + 200 °C—pleated and thermally treated at 200 °C; Fixated + 160 °C—fixated and thermally treated at 160 °C; Fixated + 200 °C—fixated and thermally treated at 200 °C.

Figure 3. Typical fracture images of (**a**) not compressed; (**b**) pleated; (**c**) fixated samples with and without thermal treatment. Abbreviations: Pleated—steamed and compressed along the grain by 20%; Fixated—pleated, then kept compressed for 5 h; TT 160 °C—thermally treated at 160 °C; TT 200 °C—thermally treated at 200 °C.

From the results of the bending test, one of the most important material properties is *MoR*. The treatments performed have a similar effect on both wood species, differing only in the extent of the change. Pleating reduces the *MoR* of the wood to a lesser extent, while fixation reduces it to almost half of the untreated wood. For uncompressed wood, *MoR* varies inversely with the intensity of thermal treatment; at 200 °C, it reduces to 62.7% for beech and 43.1% for oak. The situation is similar for pleated wood, but to a much greater extent. For fixated beech, thermal treatment at 160 °C increases *MoR* to 120.5%, while treatment at 200 °C reduces it to 26.7% compared to the values of the fixated samples. For fixated oak, thermal treatment at 160 °C increases *MoR* to 125.3%, while treatment at 200 °C reduces it to 21.5% compared to the fixated samples (Figure 4a,b).

The reason for the shown changes is the degradation of the wood as a result of thermal treatment, pleating, and fixation. At relatively lower temperatures like 160 °C, there is already a remarkable drop in the EMC (−37.8% for beech and −35.8% for oak), while cell wall degradation is only slight, resulting in only slight changes in *MoR* [32]. Decrease in EMC has a positive effect on the *MoR* [33]. Furthermore, *MoR* positively correlates with density [33]. Results show that the densities of samples that were untreated, an those of fixated and thermally treated were similar, while those that were only thermally treated at 160 °C the densities decreased for both beech and oak (Table 2). The combination of these effects, where the increase in density and the decrease in EMC improves *MoR*, while thermal degradation decreases it, resulted overall in the improvement of *MoR* in samples that were fixated and thermally treated at 160 °C, for both wood species. This finding is supported by the result that the *MoR* of samples thermally treated at 160 °C without fixation showed a clear decrease compared to untreated samples. On the other hand, in the 200 °C thermal treatment of fixed samples, the *MoR* decreased remarkably, indicating the larger thermal degradation. In these cases, it does not really matter if it is diffuse-porous beech or a ring-porous oak since the effects of the treatments are similar. In *MoR* (Figure 4a,b), similarly to the sample colors (Figure 3a), the thermal treatment at 160 °C had some minor effects: a decrease of 13.7% for beech and 4.9% for oak, with 10.2% and 13.5% higher variances compared to the variances of untreated samples, respectively. This proves that thermal decomposition and chemical changes are less intense compared to the treatment at 200 °C [32]. Since many substances disappear or transform at a temperature of 200 °C, which are also responsible for binding the strengthening components, the results are looser structures [12,16]. Different studies support the conclusion that the reason for the decrease in mechanical properties of thermally treated wood is the increase in lignin and cellulose content. However, it is also to be mentioned that this increase is only relative, due to the higher degradation rate of hemicelluloses [10,34]. Decreases in mechanical properties usually correlate with the degradation of hemicelluloses, while the changes in the structure and ratio of hemicelluloses are the main indicators for the decline in strength [35,36]. Consequently, thermally modified samples have generally weaker *MoR* compared to untreated ones and thermo-hydro-mechanically modified samples have only a fragment of the untreated values even if the 160 °C treatment improves *MoR* of fixated samples. According to previous studies [14,23], besides the effect of thermal treatment—a result of pleating and fixation—changes in the hydroxyl groups as well as in C–O and C–H functional groups of polysaccharides and lignin were observed. Beech is more sensitive to the pleating process than oak. It was concluded that although the number of hydroxyl sites did not change significantly, there were still significant differences in their location. These small chemical changes as a result of pleating and fixation are not considered to have a large effect on the mechanical properties. The decline in the bending strength as a result of pleating and fixation is rather coupled to the changes in the anatomical structure [14].

3.2.2. Bending Stress at 4 mm Deflection

The purpose of pleating is to achieve easy bending, so it is important to know how much stress is required. In addition, it is important to know how much force is required for a unit of deformation when using a wooden product made of such modified wood. The 4 mm deflection is achieved by most samples during the bending tests and is large enough that the measurement-influencing factors do not play a significant role in the results. The bending stress at the 4 mm deflection varies significantly depending on the treatments applied, compared to the bending stress of untreated wood (Figure 4c,d).

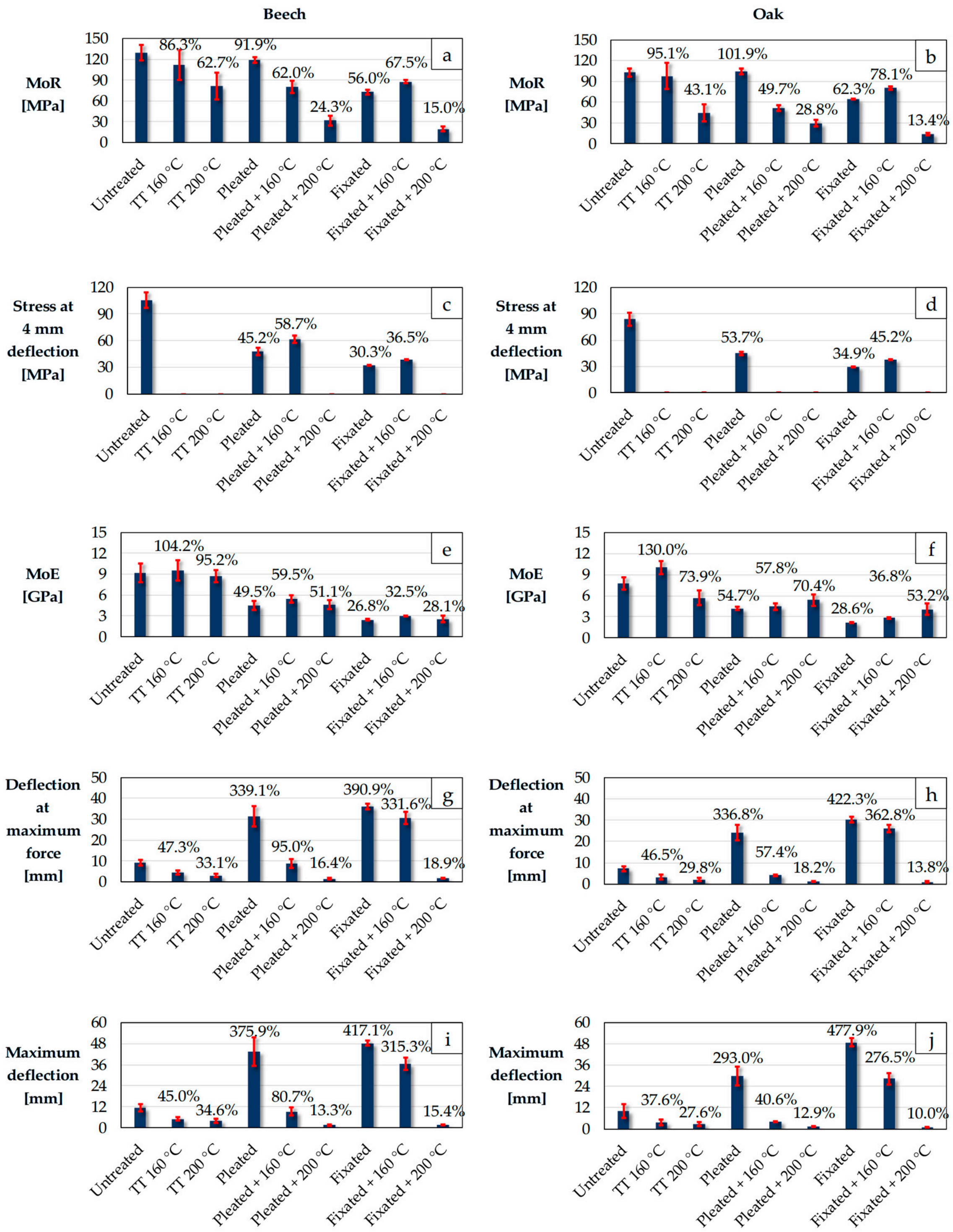

Figure 4. Diagrams based on the results of 4-point bending tests on all samples. The percentages above the columns show the differences compared to untreated samples. All diagrams show the results of different treatments for (**a**) beech *MoR*; (**b**) oak *MoR*; (**c**) beech stress at 4 mm deflection; (**d**) oak stress at 4 mm deflection; (**e**) beech *MoE*; and (**f**) oak *MoE*; (**g**) beech deflection at maximum force; (**h**) oak deflection at maximum force; (**i**) beech maximum deflection; and (**j**) oak maximum deflection. Abbreviations: *MoR*—modulus of rupture; *MoE*—modulus of elasticity; Pleated—steamed and compressed along the grain by 20%; Fixated—pleated, then kept compressed for 5 h; TT 160 °C—thermally treated at 160 °C; TT 200 °C—thermally treated at 200 °C; Pleated + 160 °C—pleated and thermally treated at 160 °C; Pleated + 200 °C—pleated and thermally treated at 200 °C; Fixated + 160 °C—fixated and thermally treated at 160 °C; Fixated + 200 °C—fixated and thermally treated at 200 °C.

Pleating halves the stress that occurs when beech wood is bent by 4 mm, fixation further reduces it to 30.3%. Thermal treatment at 160 °C increases the required stress in all cases compared to the stress before thermal treatment. None of the specimens compressed and thermally treated at 200 °C reached a deflection of 4 mm, because they broke even with a smaller degree of deflection. A total of 80% of the beech specimens treated at 160 °C reached a deflection of 4 mm, and by this point, half of the specimens had exceeded the maximum force occurring during the bending test, so these results cannot be evaluated. A total of 40% of the non-compressed beech specimens thermally treated at 200 °C reached the 4 mm deflection; the bending stress in this case reduced to 71.4% of the untreated specimens. By this time, the stress value exceeded its maximum, and the wood was damaged to some extent, meaning that these data cannot be evaluated either. Oak showed more extreme behavior: only 20% of the specimens thermally treated at 160 °C reached the 4 mm deflection, while only 10% of the pleated specimens treated at 160 °C achieved the same. Therefore, the columns representing unevaluable samples are missing from the diagrams in Figure 4c,d. Figure 2 also supports these conclusions, because it can be seen that several specimens fail before reaching the 4 mm deflection, or that the specimens reach their maximum stress before the 4 mm deflection. It would be logical to reduce the 4 mm deflection so that more samples could be included in the analysis, but this would increase the uncertainty of the analysis inherent in the initial stage of the test method.

3.2.3. Modulus of Elasticity

Thermal treatment only slightly affects the 9.16 GPa *MoE* of untreated beech wood. It appears that treatment at a temperature of 200 °C released many activated hemicellulose groups in oak, resulting in a 26.1% lower *MoE* compared to the untreated wood of 7.69 GPa (Figure 4e,f). This may be due to the degrading effect of the large amount of extractives present, which explains why no similar effect was observed in beech. In addition, at a temperature of 210 °C, a significant amount of acetic acid is released by the deacetylation of hemicelluloses, which accelerates the depolymerization of hemicelluloses and amorphous cellulose. After conditioning, in the presence of water, the density of the hemicelluloses reduces in the cell wall, along with the elasticity. At 160 °C temperature, the opposite happened, with *MoE* increasing by 30.0%. Of course, many other factors may also play a role, such as lignin, which reached its highest modulus at a 10% moisture content and may have been more dominant after the lower-temperature thermal treatment [16,29]. An in-depth chemical analysis could reveal which components changed in quantity, but this is not the subject of this study. The lower-temperature thermal treatment probably had a significant effect on hemicelluloses, but less so on lignin.

Pleating halves the *MoE* of untreated wood. Thermal treatments do not significantly affect the *MoE* of pleated beech and oak wood, but thermal treatment at 200 °C of oak causes an improvement of 28.6% compared to the *MoE* of pleated oak. The *MoE* of fixated samples (pleated, then kept compressed for 5 h) is less than 1/3 of that of untreated wood: 26.8% of the untreated beech and 28.6% of the untreated oak samples.

The situation is similar to the thermal treatment of pleated wood: thermal treatments generally do not have significant effects, except for the thermal treatment at 200 °C of oak with an 86.0% increase in *MoE* compared to fixated oak. While these data may indicate better, more shape-resistant material, in reality, it is still very fragile, similarly to the other compressed samples thermally treated at 200 °C. This can again be attributed to the decomposition of connecting substances of cell wall components and the substances connecting cells, as in previous cases. In summary, while compression significantly reduces the *MoE* of wood, thermal treatment only slightly increases it, and not even close to the initial values. The really interesting point here is the paradox observed for low *MoE*: both high plasticity and high brittleness can occur at the same time as a result of the treatments.

3.2.4. Deflection at Maximum Force

People are used to thinking that the greatest force occurs at or shortly before the point of breaking of the specimen. This is not the case when wood is compressed along the grain, which is capable of significant deformation with decreasing resistance after reaching maximum force (from which *MoR* is calculated). Thermal treatment reduces the deflection of non-compressed wood at maximum force to 47.3%–29.8%, depending on the wood species and treatment temperature (Figure 4g,h), but not to the same extent as for both pleated and fixated wood. Pleating increases the deflection at maximum force to 339.1% for beech and to 336.8% for oak. Fixation further increases these values. In contrast to fixated wood, treatment at 160 °C significantly reduces the deflection of pleated beech wood, to 28.0% for beech, and to 17.0% for oak, compared to the deflection at maximum force of pleated wood. Treatment at 200 °C further reduces it to 4.8% and to 5.4%, respectively, similarly to the wood fixated and thermally treated at 200 °C. In these cases, the effect of thermal treatment increasing rigidity is very evident. Thermal treatment at 160 °C unexpectedly reduces deflection of the fixated wood at maximum force to 84.8% for beech and 85.9% for oak, compared to non-thermally treated fixated wood. Interestingly, these results are not consistent with *MoE*, which typically quantifies the plasticity and elasticity of a material. The lower the *MoE*, the more plastic the wood becomes [37]. In this case, however, low *MoE* appears both in the samples with minimal bending capacity and in the samples with exceptionally high bending capacity. The *MoE* calculation is based on the slope of the initial section of the deformation–force graph. In some cases, such as fixated and thermally treated wood at 200 °C, this slope indicates high deflection. However, due to the structure-weakening effect of both modifications applied, the bending ends quickly as the specimen fractures rigidly.

3.2.5. Maximum Deflection

In untreated and most thermally treated specimens, fracture occurs when the maximum force is reached. In such cases, the deflection at maximum force and the maximum deflection before failure is identical. However, for specimens with greater plasticity, these are clearly distinguishable. The maximum deflection before failure measured for the compressed specimens is always greater than the deflection at maximum force. Furthermore, during the bending test, the fixated and some of the pleated specimens did not break despite the large deflection. This is because wood compressed along the grain is capable of withstanding extremely high deflections, and the bending test setup did not allow for the deflection necessary to cause failure in some specimens. Of course, based on the graphs on Figure 2a,b, the pleated specimens were closer to fracture than the fixated ones at the moment the test was stopped. This can be clearly explained by the greater degree of mechanical modification and the more significant changes in cell structure, as described in the study of Báder et al. [38]. It should be noted that the pleated oak specimens reached their fracture point at high deflection (29.96 mm, that is, 293.0% compared to the untreated oak specimens). Thermal treatment at 160 °C resulted in a clear breaking point in all cases for all specimens. As a result of the 200 °C thermal treatment, the deformation capacity and strength of all specimens were very low. Therefore, this treatment is not recommended for the modification of either compressed beech or compressed oak wood. The maximum deflection of both pleated and fixated wood was similar and the most significant, three to five times that of untreated wood (Figure 4i,j). It is important to bear in mind that the actual values are much higher than these, as there is no break in most of the specimens, so it is not worth using more accurate values. But for the other samples, the situation is clear. Thermal treatment at 160 °C reduces maximum deflection before failure of the pleated wood to 21.5% for beech and to 13.9% for oak, while treatment at 200 °C makes the deflection negligible, as was also shown at the deflection at maximum force. For fixated wood, the situation is similar for thermal treatment at 200 °C, while thermal treatment at 160 °C reduces the maximum deflection to 75.6% for beech and to 57.8% for oak, compared to fixates samples. The difference with oak wood is that the maximum deflection of pleated wood is significantly lower than that of beech. The reason for this is that, compared to beech, its less homogenic structure can lead to earlier failure at weak points, as the large ray surfaces and earlywood rings are built up of large vessels [39,40]. These samples are weakened even more intensely by thermal treatment at 160 °C.

4. Conclusions

The combined compression along the grain after steaming (also known as pleating) and thermal treatment of beech (*Fagus sylvatica*) and sessile oak (*Quercus petraea*) revealed significant modifications in mechanical and physical properties. Pleating by 20% increased plasticity and maximum deflection before failure to three to five times that of untreated wood. However, it slightly affected bending strength (*MoR*), and keeping specimen compressed for 5 h (fixation) further decreased *MoR* to nearly half of the untreated samples. The modulus of elasticity (*MoE*) fell by approximately 50% for pleated samples and to 26%–29% for fixated samples. Thermal treatment introduced temperature-dependent effects. At 160 °C, *MoR* of fixated samples increased to 120.5% (beech) and 125.3% (oak) compared with fixated-only controls, showing partial recovery of strength. In contrast, treatment at 200 °C reduced *MoR* to 26.7% (fixated beech) and 21.5% (fixated oak), reflecting severe degradation of hemicelluloses and weakened intercellular bonding. *MoE* was less affected: untreated beech (9.16 GPa) showed little change, while the *MoE* of untreated oak (7.69 MPa) increased by 30.0% at 160 °C but decreased by 26.1% at 200 °C. Compressed samples maintained very low *MoE*, with slight improvements only in oak treated at 200 °C (+86% over fixated oak).

Deflection at maximum force rose to 339% (beech) and 337% (oak) by pleating, but thermal treatment at 160 °C reduced these values to 28% and 17%, respectively, compared to pleated wood. At 200 °C, deflection dropped below 6% of pleated values, producing brittle fracture. Maximum deflection before failure confirmed this trend: pleated samples exceeded untreated wood by 293% (oak), while the 200 °C treatment rendered deformation capacity negligible.

Density increased modestly after pleating (+3.2% in beech, +1.8% in oak) but decreased after thermal treatment. At 160 °C, oven-dry density declined by 6.2% (beech) and 12.7% (oak), while at 200 °C, losses reached 18.2% and 25.1%, respectively. In combined treatments, compression significantly reduces the decomposition effects of thermal treatment.

Thermal treatment at elevated temperatures significantly impacts the mechanical and physical properties of both pleated and fixated beech and oak woods. It can reduce mechanical strength properties such as *MoR* and *MoE*. Numerical data highlights the significant impact of thermal treatment on these properties, underscoring the importance of selecting appropriate treatment conditions for specific applications. Pleated wood is primarily used in the furniture industry and interior design. With proper post-treatment, like thermal treatment, it can be used in a variety of ways like for rooms in buildings where water is used. Beech, due to its diffuse-porous structure, consistently outperformed oak in tolerating combined modification. Thermal treatment at 200 °C produces excessively brittle material unsuitable for practical use. These findings suggest that thermal treatment at 160 °C could be a good solution for pleated wood components requiring partial strength recovery and improved dimensional stability, while treatment at 200 °C should be avoided for all purposes. In the future, it may be interesting to investigate the effect of an intermediate thermal treatment temperature of 180 °C, to see if it combines the advantages of 160 °C and 200 °C treatments.

Author Contributions: Conceptualization, M.B. (Mátyás Báder) and M.B. (Miklós Bak); Methodology, M.B. (Mátyás Báder) and M.B. (Miklós Bak); Validation, M.B. (Mátyás Báder) and M.B. (Miklós Bak); Formal Analysis, M.B. (Mátyás Báder); Investigation, B.J.H.; Resources, M.B. (Mátyás Báder); Writing—Original Draft Preparation, M.B. (Mátyás Báder) and B.J.H.; Writing—Review and Editing, M.B. (Mátyás Báder) and M.B. (Miklós Bak); Visualization, M.B. (Mátyás Báder); Supervision, M.B. (Mátyás Báder) and M.B. (Miklós Bak); Project Administration, M.B. (Mátyás Báder) and M.B. (Miklós Bak); Funding Acquisition, M.B. (Mátyás Báder) and M.B. (Miklós Bak). All authors have read and agreed to the published version of the manuscript.

Funding: This paper was supported by the János Bolyai Research Scholarship of the Hungarian Academy of Sciences. Project identifier: BO/00872/23.

Data Availability Statement: Data are contained within the article.

Acknowledgments: Many thanks to Imre Horváth for preparing the specimens and to Ágnes Vörös for the help in producing the high-quality images.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Báder, M.; Németh, R. Research conditions of the wood's longitudinal compression—Part 1 (Faanyagok rostirányú tömörítésének kísérleti körülményei—1. rész). *Gradus* **2017**, *4*, 403–411.
2. Báder, M. Practical issues of longitudinally compressed wood—Part 1: The raw material and its preparation; the theory of compression (Faanyag rostirányú tömörítésével kapcsolatos elméleti és gyakorlati kérdések áttekintése—1. rész: Az alapanyagok és előkészítésük, a tömörítés elmélete). *Faipar* **2015**, *63*, 1–9. [CrossRef]
3. Báder, M.; Németh, R. Moisture-Dependent Mechanical Properties of Longitudinally Compressed Wood. *Eur. J. Wood Wood Prod.* **2019**, *77*, 1009–1019. [CrossRef]
4. Kuzsella, L.; Szabó, I. Effect of pleating on mechanical properties (A fa tömörítésének hatása a mechanikai tulajdonságokra). In Proceedings of the XI Scientific Conference for Young Engineers (Fiatal Műszakiak Tudományos Ülésszaka), Kolozsvár, Romania, 24–25 March 2006; Bitay, E., Ed.; pp. 233–236.
5. Ivánovics, G. *Strength Test of Longitudinally Compressed Wood (Rostirányban Tömörített Faanyagok Szilárdsági Vizsgálata)*; Belina, K., Ed.; College of Kecskemét: Kecskemét, Hungary, 2006; pp. 171–176.
6. Sadatneyad, S.H.; Tajvidi, M.; Yousefi, H. Effect of longitudinal compression to bulk cell wall on mechanical properties of steamed treated of beach wood. *Iran. J. Wood Pap. Sci. Res.* **2008**, *23*, 191–199. [CrossRef]
7. Sandberg, D.; Kutnar, A.; Karlsson, O.; Jones, D. *Wood Modification Technologies: Principles, Sustainability, and the Need for Innovation*, 1st ed.; CRC Press: Boca Raton, FL, USA, 2021; ISBN 978-1-351-02822-6.
8. Borůvka, V.; Zeidler, A.; Holeček, T.; Dudík, R. Elastic and Strength Properties of Heat-Treated Beech and Birch Wood. *Forests* **2018**, *9*, 197. [CrossRef]
9. Sinković, T.; Govorčin, S.; Sedlar, T. Comparison of Physical Properties of Heat Treated and Untreated Hornbeam Wood, Beech Wood, Ash Wood and Oak Wood. In *Hardwood Science and Technology, Proceedings of the 5th Conference on Hardwood Research and Utilisation in Europe, Sopron, Hungar, 10–11 September 2012*; Németh, R., Teischinger, A., Eds.; University of West Hungary: Sopron, Hungary, 2012; pp. 63–70.
10. Gaff, M.; Kačík, F.; Gašparík, M. Impact of Thermal Modification on the Chemical Changes and Impact Bending Strength of European Oak and Norway Spruce Wood. *Compos. Struct.* **2019**, *216*, 80–88. [CrossRef]
11. Korkut, S.; Karayilmazlar, S.; Hiziroglu, S.; Sanli, T. Some of the Properties of Heat-Treated Sessile Oak (*Quercus petraea*). *For. Prod. J.* **2010**, *60*, 473–480. [CrossRef]
12. Gaff, M.; Kačík, F.; Sandberg, D.; Babiak, M.; Turčani, M.; Niemz, P.; Hanzlík, P. The Effect of Chemical Changes during Thermal Modification of European Oak and Norway Spruce on Elasticity Properties. *Compos. Struct.* **2019**, *220*, 529–538. [CrossRef]
13. Yilmaz Aydin, T.; Aydin, M. Influence of Temperature and Exposure Duration on the Bending Properties of Oak Wood. *Bartın Orman. Fakültesi Derg.* **2020**, *22*, 871–877. [CrossRef]
14. Báder, M.; Németh, R. A Review of Wood Compression along the Grain—After the 100th Anniversary of Pleating. *Forests* **2023**, *14*, 763. [CrossRef]

15. Stevens, W.; Turner, N. *Solid and Laminated Wood Bending*; Forest Products Research Laboratory, Department of Scientific and Industrial Research; His Majesty's Stationery Office: London, UK, 1948.
16. Hill, C.; Altgen, M.; Rautkari, L. Thermal Modification of Wood—A Review: Chemical Changes and Hygroscopicity. *J. Mater. Sci.* **2021**, *56*, 6581–6614. [CrossRef]
17. Jančíková, V.; Jablonský, M. Thermal Modification of Wood—A Review. *Sustain. Chem.* **2025**, *6*, 19. [CrossRef]
18. *ISO 13061-03*; Physical and Mechanical Properties of Wood—Test Methods for Small Clear Wood Specimens—Part 03: Determination of Ultimate Strength in Static Bending. ISO: Geneva, Switzerland, 2014.
19. Sedlar, T.; Šefc, B.; Stojnić, S.; Jarc, A.; Perić, I.; Sinković, T. Tvrdoća Toplinski Modificirane Bukovine i Grabovine. *Šumar. List.* **2019**, *143*, 433. [CrossRef]
20. Dudiak, M.; Dzurenda, L. Changes in the Physical and Chemical Properties of Alder Wood in the Process of Thermal Treatment with Saturated Water Steam. *Coatings* **2021**, *11*, 898. [CrossRef]
21. Taraborelli, C.; Monteoliva, S.; Keil, G.; Spavento, E. Effect of Heat Treatment on Hardness, Density and Color of Populus × Canadensis 'I-214' Wood. *For. Syst.* **2022**, *31*, e023. [CrossRef]
22. Borrega, M.; Kärenlampi, P.P. Hygroscopicity of Heat-Treated Norway Spruce (*Picea abies*) Wood. *Eur. J. Wood Wood Prod.* **2010**, *68*, 233–235. [CrossRef]
23. Báder, M.; Németh, R.; Sandak, J.; Sandak, A. FTIR Analysis of Chemical Changes in Wood Induced by Steaming and Longitudinal Compression. *Cellulose* **2020**, *27*, 6811–6829. [CrossRef]
24. Herrera-Builes, J.F.; Sepúlveda-Villarroel, V.; Osorio, J.A.; Salvo-Sepúlveda, L.; Ananías, R.A. Effect of Thermal Modification Treatment on Some Physical and Mechanical Properties of Pinus Oocarpa Wood. *Forests* **2021**, *12*, 249. [CrossRef]
25. Gustafsson, S. The Strength Properties of Swedish Oak and Beech. *Drew. Pr. Nauk. Doniesineia Komun.* **2010**, *53*, 67–83.
26. Muñoz, G.; Gete, A. Prediction of Bending Strength in Oak Beams on the Basis of Elasticity, Density, and Wood Defects. *J. Mater. Civ. Eng.* **2012**, *24*, 629–634. [CrossRef]
27. Costa, H.W.D.; Coldebella, R.; Andrade, F.R.; Gentil, M.; Correa, R.; Gatto, D.A.; Missio, A.L. Brittleness Increase in *Eucalyptus* Wood after Thermal Treatment. *Int. Wood Prod. J.* **2020**, *11*, 38–42. [CrossRef]
28. Nakagawa, T.; Poulin, E.; Rueppel, T.; Chen, Z.; Swinea, J.; O'Brien, M.; Houser, G.; Wood, G.; Weinheimer, M.; Bahmani, P.; et al. Effects of Thermal Modification on the Flexure Properties, Fracture Energy, and Hardness of Western Hemlock. *Wood Sci. Technol.* **2024**, *58*, 109–133. [CrossRef]
29. Kubovský, I.; Kačíková, D.; Kačík, F. Structural Changes of Oak Wood Main Components Caused by Thermal Modification. *Polymers* **2020**, *12*, 485. [CrossRef] [PubMed]
30. Wang, J.; Minami, E.; Asmadi, M.; Kawamoto, H. Effect of Delignification on Thermal Degradation Reactivities of Hemicellulose and Cellulose in Wood Cell Walls. *J. Wood Sci.* **2021**, *67*, 19. [CrossRef]
31. Buchter, J.; Adelhoej, J.; Ljoerring, J.; Hansen, O. *Introducing Compressed Wood*; Danish Technological Institute, Department of Wood and Furniture: Taastrup, Denmark, 1993.
32. Bytner, O.; Drożdżek, M.; Laskowska, A.; Zawadzki, J. Influence of Thermal Modification in Nitrogen Atmosphere on the Selected Mechanical Properties of Black Poplar Wood (*Populus nigra* L.). *Materials* **2022**, *15*, 7949. [CrossRef]
33. Niemz, P.; Teischinger, A.; Sandberg, D. (Eds.) *Springer Handbook of Wood Science and Technology*; Springer Handbooks; Springer International Publishing: Cham, Switzerland, 2023; ISBN 978-3-030-81314-7.
34. Rogério Da Silva, M.; Otávio Brito, J.; Silvio Govone, J.; De Oliveira Machado, G.; Calil Junior, C.; Luis Christoforo, A.; Antonio Rocco Lahr, F. Chemical and Mechanical Properties Changes in Corymbia Citriodora Wood Submitted to Heat Treatment. *Int. J. Mater. Eng.* **2015**, *5*, 98–104. [CrossRef]
35. Boonstra, M.J.; Van Acker, J.; Tjeerdsma, B.F.; Kegel, E.V. Strength Properties of Thermally Modified Softwoods and Its Relation to Polymeric Structural Wood Constituents. *Ann. For. Sci.* **2007**, *64*, 679–690. [CrossRef]
36. Sweet, M.S.; Winandy, J.E. Influence of Degree of Polymerization of Cellulose and Hemicellulose on Strength Loss in Fire-Retardant-Treated Southern Pine. *Holzforschung* **1999**, *53*, 311–317. [CrossRef]
37. Sandberg, D.; Kutnar, A.; Mantanis, G. Wood Modification Technologies—A Review. *IForest-Biogeosci. For.* **2017**, *10*, 895–908. [CrossRef]
38. Báder, M.; Németh, R.; Konnerth, J. Micromechanical Properties of Longitudinally Compressed Wood. *Eur. J. Wood Wood Prod.* **2019**, *77*, 11. [CrossRef]
39. Stanzl-Tschegg, S.E. Microstructure and Fracture Mechanical Response of Wood. *Int. J. Fract.* **2006**, *139*, 495–508. [CrossRef]
40. Sonderegger, W.; Martienssen, A.; Nitsche, C.; Ozyhar, T.; Kaliske, M.; Niemz, P. Investigations on the Physical and Mechanical Behaviour of Sycamore Maple (*Acer pseudoplatanus* L.). *Eur. J. Wood Wood Prod.* **2013**, *71*, 91–99. [CrossRef]