Relationship between the Fixation Period and Some Mechanical Properties of Pleated Wood

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Abstract. Longitudinally compressed wood (or pleated wood) is much easier bendable compared to untreated wood, even to much smaller curves. Its properties make pleated wood both an economically and environmentally friendly product for performing curved wood products. As a result of longitudinal compression, modulus of elasticity and required bending stress highly decrease, while bendability coefficient increases threefold. The longitudinal compression is usually followed by the fixation process: the degree of compression is held constant for a certain amount of time to relax the internal stresses in the wood. Fixation strengthens the effects of the treatment and it is used by the industry, but unfortunately, there is very slight literary knowledge available in this topic. We try to fill this gap by using different times of fixation and bending tests. The first minute of fixation is the most effective, but for example fixation for more than 10 hours results in a maximum deflection during 4-point bending tests of 675%, in a decrease of modulus of elasticity to 18.6% and in a decrease in bending stress at 5 mm crosshead displacement to 29.3%, compared to untreated specimens. Finally, pleated wood can undergo significant plastic deformation before fracture.

1. Introduction
The first step prior to the longitudinal wood compression is the plasticization process. Without plasticization, the structure of wood would be destroyed as in a compression test. The plasticization process is done usually using saturated water steam; this way, the moisture content of wood gets closer to the fiber-saturation point. The compression can be performed in a device that can hold the sides of the sample straight, while it presses end-grains of the sample. In the course of longitudinal compression, the cell walls fold and become wavy like a plisse shade. Based on this similarity this modified wood material is also known as pleated wood (Figure 1).

The process results in easily and highly bendable wood. It can be bent using smaller forces and also in smaller curves by pleating, even when it is cold, compared to both untreated wood and steamed wood [1, 2]. Longitudinally compressed wood can be held in stock and can be easily used as an element in serial production. Compared to traditional technologies, this material requires much less industrial processing, thus, producing curved surfaces using pleated wood results in minimal loss of material. Therefore, pleated wood is both an economically and environmentally friendly product without added chemicals and reduced waste material. Conventional tools can be used for the processing of this material (sawing, surface-planing, sanding, etc.) [3]. After drying, pleated wood preserves its new shape until it is held in dry conditions [4, 5]. Pleating and the following bending process requires high quality hardwood raw material (narrow annual rings, defect free, straight grained) [2, 5, 6]. To avoid unwanted damages of wood during compression, the moisture content of the sample must be kept above its fiber-saturation point [7]. The ratio of compression is usually 20% compared to the original
length of the sample. After compression, the sample can be held for a while constantly at the applied compression level. This period is called fixation, because the compressed length of the wood is fixated for a predetermined time. The compressed sample is easily bendable until its moisture content is high [6].

![Figure 1. Scanning electron microscopy image of sessile oak, showing in magnification ×300 the buckling of a trachea’s wall due to the longitudinal compression (based on [8]).](image)

The patent of Hanemann [9] was the first which described this method in 1917. This was an alternative to the steam-bending technology of Thonet, upgrading the properties of the product. Nowadays, compressing machines working in Hungary, Italy and in the USA. The products are parts of chairs and skirting, furniture rims, mattress coil springs, etc (furniture industry); wooden handrails, coat hooks, applied arts, etc. (interior design); other applications e.g. vibration-dampening tool shafts, car panels, wood toys, medical aids, shoe insoles [6]. Since its patenting, scientific data on pleated wood has been published in many places. It is already known that the mechanical properties of this modified wood are influenced by a number of factors, such as wood species, degree of compression, duration of fixation, moisture content, etc. Unfortunately, the published results are generally unreliable because most publications lack some of the important information. In table 1 the changes of modulus of rupture (MoR) and the modulus of elasticity (MoE) can be seen due to pleating. The source articles do not always provide detailed conditions of the details of the researches, so these results need to be treated carefully. But the trends are unequivocally similar, both the MoR and the MoE significantly decrease (Table 1).

| Author            | MoR Beech (%) | MoR Oak (%) | MoE Beech (%) | MoE Oak (%) |
|------------------|--------------|------------|---------------|------------|
| Buchter et al. [5] | -10.0        | -15.0      |               |            |
| Ivánovics [10]    | -45.8        | -42.1      | -68.1         | -60.0      |
| Kuzsella and Szabó [11] | -47.2      | -16.8      | -69.5         | -45.4      |
| Candidus [12]     | -27.5        |            | -64.5         |            |
| Báder and Németh [13] | -21-25    | -58-62     | -61-64        |            |
| Báder and Németh [2] | -19.2       | -46.0      | -            |            |

All publications in table 1 have been produced in the recent decades. Earlier authors, for example Vorreiter [14, 15] or Kollmann [16], described this material in general terms, without giving specific
results. This study has been prepared to determine the changes of some physical and mechanical properties (compression stress, remaining shortening, MoE, etc.) of oak wood due to longitudinal compression by 20%, followed by different periods of fixation. In this way the effect of fixation can be clearly identified.

2. Materials and methods

2.1. Longitudinal compression and fixation

The raw material of this study was Hungarian Sessile oak (Quercus petraea (Matt.) Liebl.). The freshly cut boards were processed into samples with dimensions of 20 × 20 × 200 mm³ (radial × tangential × longitudinal directions) determined by the laboratory-scale compressing device, from the same trunk. The samples were frozen until the time of use to keep their moisture content (MC). The samples contained only defect-free oak heartwood with narrow annual ring widths and minimal fiber slope, cut from a straight grown tree [17]. During the treatment, the samples were first plasticized in saturated water steam at atmospheric pressure. Right after plasticization, the samples were compressed in their longitudinal direction in a heated laboratory device by 20% compared to their original length, with a compression rate of 15 m·(m·h)⁻¹ [13]. The samples were kept straight during the compression process, through the lateral steel supports on the sides. The supports ensure the samples to do not increase in their cross-sectional size and to keep them straight. During the process at least 80 °C temperature should be maintained throughout the entire cross section of the sample, to be able to compress the sample without breaks and cracks. The semi-closed laboratory equipment allows minimal contact of sample with air. The device is individually produced and developed to operate in an Instron 4208 universal material testing machine (Instron Corporation, USA). The properties of longitudinally compressed wood can be mostly influenced through the compression ratio and the time of fixation [6]. In this study, the fixation period and its results are in focus, so the compression ratio of the samples were held compressed for different periods; table 2 shows the used methods and the sample numbers.

| Marking | Pieces | Sample marking explanation |
|---------|--------|----------------------------|
| OC      | 20     | Control (untreated)        |
| O0m     | 20     | Compressed without fixation|
| O1m     | 20     | Compressed with fixation for 1 minute|
| O3m     | 18     | Compressed with fixation for 3 minutes|
| OLm     | 3      | Compressed with fixation for a long time (averagely 900 minutes) |

All fixations were performed in the heated laboratory compression device. In case of the OLm samples the heating was switched off during the fixation, to let the system with the sample cool down, and thus eliminate the loss of moisture. After the described pleating, the samples were conditioned at 20 °C temperature and 65% relative humidity (RH) until a constant weight was reached.

2.2. Bending test

Macromechanical experiments were made with pleated wood after conditioning to get the discrepancies that different treatments initiate. 4-point bending tests were carried out. Since the goal of longitudinal compression is high bendability, we used a unique support-span/specimen-thickness ratio to be able to reach the failure point of the specimens. The originally quadratic cross sections were changed to rectangular for the bending test: untreated specimens (OC) were prepared averaging 19.3 × 12.7 × 200.3 mm³ (R × T × L); O0m, O1m, O3m specimens were prepared averaging 19.1 × 12.9 × 192.1 mm³ (R × T × L) and compressed specimens fixated for a long time (OLm) were prepared averaging 19.7 × 12.6 × 167.2 mm³ (R × T × L). The annual rings were vertically oriented during the bending examinations. A universal material testing machine (Instron 4208, Instron Corporation, USA) was used, equipped with a static load cell of 300 kN maximum capacity. The loading rate was 8
mm·min\(^{-1}\) for untreated specimens and 16 mm min\(^{-1}\) for pleated specimens because of the much higher pliability, following the instructions of the standards MSZ 6786-5 and ISO 13061-3 [18, 19]. Tests were stopped upon failure, when the load dropped with no recovery. As Hein and Brancheriau [20] described, the test volume under stress for 4-point bending is bigger than that under 3-point bending, so it gives more relevant average results. To be able to compare the stress necessary for bending untreated and treated specimens, it is essential to use the same deflection (or bending radius). 5 mm is a crosshead displacement where only a small proportion of specimens breaks in the course of a bending test, but the bending stress \(BS_{\text{5mm}}\) is already not negligible (Equation 1). Comparing these values, it can be seen how much easier it is to bend pleated wood than untreated wood.

\[
BS_{\text{5mm}} = (3 \cdot F \cdot a) / (b \cdot h^2)
\]

(1)

where \(F\) is the load, and \(a\) is 50 mm, the distance between the loading roller and the nearest support roller. The upper span was 50 mm. If we take into account natural wood samples, the elastic part of the displacement-load plot belongs to the 10-40% of the maximum force, but for pleated wood the elastic part of the plot is shorter. \(MoE\) was calculated based on the work of Kossa [21] using the crosshead displacement (\(\Delta w\)) corresponding to the difference between the 10% and 25% of the maximum load (\(\Delta F\)), in order to remain in the elastic range of this material (Equation 2).

\[
MoE = [\Delta F \cdot a^2 \cdot (3 \cdot L - 4 \cdot a)] / (b \cdot h^3 \cdot \Delta w)
\]

(2)

where \(L\) is the lower span (150 mm). The highest deflection during bending test (\(y_{\text{max}}\)) came from Kossa [21] with a necessary amendment, since pleated wood has high deflection (Equation 3).

\[
y_{\text{max}} = 1.1563 \cdot [w \cdot (3 \cdot L^2 - 4 \cdot a^2)] / [4 \cdot a \cdot (3 \cdot L - 4 \cdot a)] - 0.7345
\]

(3)

where \(w\) is the maximum crosshead displacement. Between the measured deflection and the calculation, the statistical coefficient of correlation is \(R^2=0.9995\). Another descriptive parameter for the pliability of pleated wood is the bendability coefficient \(k_{\text{bend}}\) [22] (Equation 4).

\[
k_{\text{bend}} = 8 \cdot h \cdot y_{\text{max}} / L^2 + 4 \cdot y_{\text{max}}
\]

(4)

Finally, the specimens were dried in an oven at a temperature of 103°C to determine their \(MC\) at the time of the bending tests.

3. Results and discussion

3.1. Experiences of experiments

In the course of the fixation, the compression stress decreases quickly at first and then this decrease gradually slows down but still goes on even after many hours as the sample cools down in the compressing device. In Figure 2 the time - stress plot for a compression and fixation for 5 minutes can be seen. Thus, the greatest change in the compression stress happens in the first minute of the fixation. Regarding fixation, it is known that after longitudinal compression of wood, thick-walled fibers have significant remaining changes, while the cells with thin walls more easily recover the original smooth shape of cell-wall after the pressure load is removed. This phenomenon is caused by the spring-back property of wood. After fixation for a long time, both thick-walled and thin-walled cells of the wood suffer permanent changes. These changes can be seen on microscope images as wavy-like folds, also known as buckling, as shown in figure 1. With increasing fixation time, the remaining shortening increases, so the buckling of the cell walls increases.

After conditioning and cutting with a circular saw, the \(MC\) of the specimens were 14.1±0.4%. This was their average \(MC\) at the time of the bending tests.
3.2. Mechanical properties

The MoE of the untreated specimens was averagely 10.0 GPa, while the literature gives 9.2-13.0-13.5 GPa [23], 12.3 GPa [24] and 10.47 GPa [25] for oak wood. The reason of this result can be the less good region where the wood comes from, the natural diversity of wood or the different test method between the 3 and the 4-point bending tests. These differences between raw materials and test setups can cause such deviations for all properties. The bending stress needed for the 5 mm crosshead displacement ($BS_{5mm}$) was 100.0 MPa for untreated specimens and bendability coefficient ($k_{bend}$) was 0.04. The effects of the different treatments on remaining shortening, MoE, $BS_{5mm}$ and $k_{bend}$ are shown in figure 3.

The stress at 5 mm crosshead displacement approximately halved by longitudinal compression (Figure 3: Bending stress), this shows us the first advantage of the pleating method: the force needed to bend the same the radius, decreases considerably. Longitudinal compression without fixation resulted in a remaining shortening of 3.6%, in a decrease of MoE with 59.0% and in a three-fold increase in $k_{bend}$ to 0.12. Pliability has a strong inverse correlation with MoE [26], this can also be observed here. The deflection during bending tests of untreated specimens averaged 9.3 mm till their failure. Both compressed specimens and specimens fixated for a short-time had more than 3 times higher deflection, requiring almost the same bending force to reach the failure point. The effect of fixation for a short time after compression results in changes visible well in figure 3.

Figure 2. A typical time - stress plot of a longitudinal compression followed by a fixation for 5 minutes [2].

Figure 3. The changes in some physical and mechanical properties of oak wood as a result of pleating.
Using fixation for 1 minute (O1m) and for 3 minutes (O3m) resulted in an increase of remaining shortening of 0.62% and 0.98%, in a reduction of MoE of 4.44% and 7.26%, in a reduction of BS\text{sum} of 2.85% and 5.24% and in an increase of k\text{bend} of 10.87% and 24.29%, respectively, compared to compressed (O0m) specimens (Figure 3). Calculating the changes resulted by fixation on unit of time, the most significant change for each described property is shown in the first minute. Performing a fixation for a long time (OLm), it increases the effect of longitudinal compression by 12.84% for remaining shortening, by 22.90% for MoE, by 17.43% for BS\text{sum} and by 111.86% for k\text{bend} (Figure 3). With a large increase of fixation time the deflection of the specimens increased so much that they could not be broken during the bending tests. High deflection indicates high bendability, which is the aim of this treatment. For OLm specimens the maximum deflection is more than 675% compared to untreated specimens. OLm specimens show ductile properties, because they can undergo significant plastic deformation before fracture [27]. In figure 4 the OLm specimen is the most curved, but no fracture can be observed on it. Summing up the data of figure 3, both longitudinal compression and compression followed by a fixation for a long time dramatically alter the properties of wood. All the described varied properties led to a new material with the major advantage of easy pliability.

![Figure 4](image-url)

**Figure 4.** A comparison of typical oak wood specimens after bending tests, as a result of pleating followed by different periods of fixation [28]. Abbreviations: OSC – steamed but uncompressed specimen; O0m – longitudinally compressed specimen; O1m – longitudinally compressed specimen fixated for 1 minute; OLm – longitudinally compressed specimen fixated for a long time.

### 3.3. Optimal time of fixation

The time-stress plot on figure 2 shows a typical result: during the fixation phase, the graph is always continuous and has no breakpoint. Analysing the change of compression stress over time, in the first two seconds of the fixation the compression stress falls by 12.1%. In the next two seconds of the fixation, the compression stress falls by 4.7%, then only by 3.1% and by 2.4%, compared always to the initial value. Looking further, the degree of decrease is approaches to zero, but never reaches it. Similarly to a kind of exponential functions, which is strictly monotonic and always approaches to a constant value. Since the time of fixation highly affect the properties of the product, of course, the time of fixation have to be chosen to meet the individual demands. A fixation for a long time is necessary to reach the maximum deflection of the wood, but this is a very slow, time-demanding process both for industrial and laboratorial production. However, pliability increases a lot (Figure 3). Thus, it is impossible to determine the ideal fixation time due to different needs, but we can make a recommendation for choosing the minimum fixation period. Compared with the initial decrease of compression stress in two seconds (12.1%), a value of 0.5% should be taken into account as it is considerably smaller, about only one-twentieth of it. When the decrease will constantly below 0.5% per two seconds, the change of compression stress can be considered as slow. By using this experiential value, both productivity and required properties meet practice. The results of the calculations are shown in table 3.

If we are looking for the minimal time of fixation based on the decrease of compression stress which correlates with the mechanical changes, a fixation for one minute is suggested. Fixation for one minute also has a safety reserve, because averagely 50 seconds would be enough (Table 3). After a fixation for one minute, the maximum deflection increases to 110% compared to the longitudinally compressed wood specimens without fixation, and to 353% compared to the untreated specimens. This is in
accordance with the decrease of MoE (89.3% and 37.0%, respectively) and the $k_{bend}$. In this fixation period compression stress decreases to 67.4% and bending stress at 5 mm crosshead displacement decreases to 43.9% as a result of longitudinal compression followed by fixation for 1 minute, compared to the untreated specimens.

Table 3. The time of fixation when the change of compression stress is below 0.25% per second. Abbreviations: O1m, O3m - longitudinally compressed oak specimens with 1 and 3 minutes of fixation time; OLm-compressed oak specimen fixated for a long-time.

| Treatment marking | Average  | Coeff. of var. | Minimum | Maximum |
|-------------------|----------|----------------|---------|---------|
| O1m               | 48.9     | 17.3%          | 33.5    | 59.1    |
| O3m               | 51.6     | 20.4%          | 31.7    | 69.5    |
| OLm               | 47.1     | 28.4%          | 35.5    | 61.8    |
| Total:            | 49.8     | 19.9%          | 31.7    | 69.5    |

4. Conclusions
The properties of longitudinally compressed wood are influenced by many factors. One of the most important factors is the time of fixation, which means that the how long is the sample held compressed after reaching the specified compression ratio. As a result of this treatment (also known as pleating due to the deformations of the cell walls) wood will be more easily bendable in smaller curves, compared to untreated or freshly steamed wood. Selected physical mechanical properties were investigated (remaining shortening, modulus of elasticity, bending stress and bendability coefficient) using different specimens: untreated, compressed in its longitudinal direction, compressed and fixated for 1 or 3 minutes, compressed and fixated for a long time. During fixation, the compression stress decreases continuously. After 1 minute of fixation the change of the compression stress as well as the change of material properties slow down, thus, the recommended minimum fixation time is 1 minute as an ideal combination of economic fixation time and increasing of bendability. This results in a maximum deflection during 4-point bending tests of 353%, in a decrease of modulus of elasticity to 37% and in a decrease in bending stress at 5 mm crosshead displacement to 44%, compared to untreated specimens. To meet special requirements for the product, both the compression ratio and the time of fixation can be varied. Fixation for a long time results in a wood material with approximately plastic properties. It achieves a more than 6 times higher deflection compared to untreated wood, still without breaking, but slows down the production and increases the costs.

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