Spring-back of Wood after Longitudinal Compression

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Abstract. Longitudinal compression of natural wood makes it easier to bend. Fixation after compression results in improved changes in the properties of this environmentally friendly material. The usage of this modified wood helps to make curved wood products with much less waste, without chemicals. Using 20% compression ratio followed by fixation for 1 minute results in optimal properties for laboratory investigations. As a result of this treatment, oak wood is shortened averagely by 3.84% due to its natural spring-back ability. The aim of this study is to determine not only the level, but the duration of spring-back of wood after its longitudinal compression. Wood remains always a living organism with a natural structure, actively responding to environmental conditions such as temperature and humidity of the air. Its moisture content follows the circumstances and changes its properties, for example, it shrinks when its moisture content decreases. Longitudinal compression (aka pleating) multiplies the dimension change of wood in its longitudinal direction, compared to untreated wood. In this study, the remaining shortening of pleated wood was averagely 5.50% after spring-back and drying shrinkage.

1. Introduction

Wood modification is a process that improves the properties of wood, producing a new material that does not present any environmental hazard greater than unmodified wood when disposed at the end of its product life cycle [1]. Longitudinal compression of wood (also known as pleating) is an interesting technology, which makes this natural fiber reinforced composite material easier to bend. The modification treatment results in a well-pliable wood raw material, pre-processed for industrial applications. It can be bent even in room-temperature conditions until its moisture content (MC) is over about 20% and it can be held in stock. This is important when this material is used as an element in serial production. Producing curved surfaces from compressed wood results in minimal loss of material, compared to traditional technology. This makes pleated wood a highly environmentally friendly material. Disturbing lines of joints on the product-surfaces can be avoided, because many parts can be made of one piece of wood [2]. Conventional tools can be used both for the processing (sawing, surface-planing, sanding, etc.) and bending [3]. After drying, pleated wood preserves its new shape [4, 5]. Using slightly different technologies, it is currently produced in Italy, in Hungary and in the USA [6]. This is an excellent raw material for the furniture industry, for interior design, and for areas where sharp corners are not allowed for safety reasons (ship and aircraft furniture) [7].

The pleating results in an increase in maximum pliability by at least 350%, and in a decrease to 37% in bending modulus of elasticity (MoE) and to 44% in bending stress at small deflections compared to the control samples [6]. This means the process ensures high deformability for wood even with a dramatically decreased bending force. Prior to the compression procedure, the both high-density and high-quality hardwood has to be plasticized by steaming. After longitudinal compression, the sample is first wet. The plasticization process means the softening of the bonds of hemicelluloses and lignin,
so the binding force between cells of wood decreases. Softening of wood in hot and humid conditions is needed [8]. The wood is compressed usually by 20% compared to its original length. During longitudinal compression, the sample can be held for a predetermined time constantly at the applied compression level. This period is called fixation, because the compressed length of the wood is fixated for a predetermined time. In this period, the stresses caused by the longitudinal compression of wood are relaxed and finally - depending on the duration of this period - the longitudinal deformation partially or completely remains after treatment (Figure 1a). Compression stress increases during the compression process and decreases continuously in the fixation phase with gradually decreasing intensity (Figure 1b). Fixation increases the effects of the longitudinal compression, the most important is that the MoE further decreases along with increasing fixation time: the decrease in the MoE as a result of longitudinal compression is 59%. Its decrease due to compression followed by fixation for 1 minute is 63%, and if fixation is used for more than 10 hours after compression, the MoE decreases by 81%. Each value is with a uniform MC of 12% [6]. The cell walls of wood can be considered originally smooth-surfaced, but as a result of the treatment the buckling of the cell walls occurs. This is the reason why the method of longitudinal compression and fixation is called pleating.

![Figure 1](image_url)

**Figure 1.** Shortening of samples as a result of different longitudinal compression settings (a) and a typical time - stress plot of a longitudinal compression followed by a fixation for 5 minutes (b) [9, 10].

Abbreviations: OC – untreated sample; O0m – longitudinally compressed sample; O1m – longitudinally compressed sample fixated for 1 minute; OLm – longitudinally compressed sample fixated for 18 hours.

The memory effect, or shape memory effect is defined as a dominant feature of smart materials. These materials are capable to keep a temporary shape received as a result of deformation under certain conditions. But the sample remembers its earlier shape and there is always a possibility to return to its original shape, or near to its original shape, which has been also called as set-recovery. Accordingly, the sample remembers at least two forms [11, 12]. Nevertheless, spring-back is a natural reaction of the wood to the release stresses imposed during an operation [13]. The difference between the memory effect and the spring-back is that spring-back occurs immediately as soon as the stress causing the deformation is eliminated, thus, the sample shows an immediate set-recovery. In a previous study, relationship was found between the change of compressive stress during fixation following the longitudinal compression, the remaining shortening and selected mechanical properties. Increasing fixation time increases the remaining shortening of a sample, so its spring-back will be much weaker [6]. The spring-back correlates well with the change of the compression stress during fixation, the MoE and the bendability. Fixation for a long time results in a more effective treatment, but it consumes much more time. Thus, it may be used only if extreme wood properties are necessary after this modification process. Considering the effective property changes, the productivity and the
costs, the ideal fixation time was specified as 1 minute by Báder and Németh [6], but it depends on the requirements regarding the product properties. For pleated wood, spring-back is the opposite of the remaining shortening. Báder and Németh [14] found that after compression, the sample springs back and the remaining shortening will be usually about 3-5%. If an oak sample has been compressed by 20% compared to its original length and released immediately, its remaining shortening will be averagely 2.49%. In case of 1, 3 and 1 500 minutes of fixation the remaining shortening will be 3.04%, 3.49% and 19.01%, respectively [15]. Beech shows always greater spring-back. The fiber-saturation point (FSP) is a moisture level of a wood, when all intermicellar and interfibrillar cavities (the cell walls) expand and are fully saturated with water, but the cell lumens contain no free water. It follows that if the wood absorbs more water, it will no longer affect the cells, it will only be in the wood as free water. This way free water can not cause any change in the physical dimensions of the wood. FSP has a different value for each wood species, ranging from about 20 to 35% MC. For oak wood, FSP is 24.5% [16]. Below FSP with decreasing MC the mechanical properties of wood increase, while the dimensions of the wood decrease. This decrease can be maximal about 10-12% in the radial direction, 5-6% in the tangential direction and 0.1-0.3% in the longitudinal direction, depending on the properties of the wood species. It is worth to mention that after longitudinal compression, shrinkage is three times higher during drying, compared to untreated samples. Fixation further increases the shrinkage, in the first minute from 0.51% to 0.68%. With the samples fixated for a long-time, the shortening amounts to 0.94% during drying, which means about six times higher shrinkage compared to untreated samples. This phenomenon is due to the buckled cell walls (Figure 2), because buckling adds a part of the far greater transverse shrinkage of wood to its longitudinal shrinkage [9]. This study has been done to determine, demonstrate and describe the spring-back property of oak wood over time after the longitudinal compression treatment.

![Figure 2](image)

**Figure 2.** Scanning electron microscopy image of a pleated wood shows buckled cell walls (based on Báder et al. [15]).

2. Materials and methods

2.1. Longitudinal compression and fixation

The raw material of the experiment was Sessile oak (*Quercus petraea* (Matt.) Liebl.) came from the Sopron region, Hungary. 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 MC. Prior to the treatment, 20 wet samples were randomly selected. The samples contained only defect-free oak heartwood with slightly differing annual ring widths and minimal fiber slope. 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 unique laboratory device by 20% compared to their original length, with a relative compression rate of 15 m·(m-h)^{-1} [17]. The relative rate of compression (m·(m-h)^{-1}) uses basic units to show how much shortening would occur in a 1-meter-long section of the workpiece during a 1-hour compression process. In this way it is possible to compare the rate of laboratory measurements with different industrial-scaled treatments. During our measurements, the 15 m·(m-h)^{-1} relative rate of compression on 200 mm long samples meant a 50 mm/min crosshead displacement. The time of fixation was 1 minute, so the whole pleating process took 110 seconds. The MC of the samples at the time of pleating was consistently over their fiber saturation point. Pleating is a thermo-hydro-mechanical modification process. 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 workpiece was kept straight during compression, through heated supports on the sides. This way the increase in cross-sectional size was avoided and the sample was kept straight. 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).

2.2. Measurement of sample properties
The mass of the samples was measured with a Precisa XT 1220M-FR scale (Precisa Instruments AG., Switzerland), measures grams to an accuracy of three decimal places. They were later dried in a Memmert 100–800 oven (Memmert GmbH, Germany) at 103 ± 2 °C according to standards MSZ6786-2 and ISO13061-1 [18, 19], and then the absolute dry mass was measured. Using these results, the MC of the samples could be calculated at the time of the tests. The dimensions of the samples were measured using a digital Helios digital indicator (Helios-Preisser GmbH, Germany) connected to a computer. The digital indicator measures millimetres to an accuracy of three decimal places. According to the purpose of the investigation, both mass and length of each sample were measured at 0.5, 1, 1.5, 2, 3, 4, 5, 10, 15, 30, 60, 120 and 240 minutes after the completion of the treatment. 0.5 minute is the first measurement time since it takes time to remove a sample from the compressing device and to perform the measurements. The dimensions in the other two anatomical directions were measured after 5, 60 and 240 minutes. Further, the mass and all dimensions of the samples were measured at 6, 25, 118, 170, 261, 307, 423, 495 and 596 hours after the treatment. The samples were climatized between 4 and 118 hours at 20 °C and 65% relative humidity (RH). Then, between 118 and 307 hours at 30 °C and 50% RH, between 307 and 423 hours at 20 °C and 40% RH, between 423 and 495 hours at 60-80 °C with gradual increase and 50% RH, between 495 and 596 hours at 103 °C to get the absolute dry state of the samples.

3. Results and discussion
After the preliminary measurements it was realized that the mass measurement of the samples in the first minutes after the treatment is unnecessary, because the initial MC of the samples was about 60% and the loss of moisture cannot cause physical changes highly over the FSP of the wood [16]. But still, stresses remain in the material after pleating, so a change in length can be expected, as it is evidenced by table 1.

| Time [min] | 0.0 | 0.5 | 1.0 | 3.0 | 5.0 | 15.0 | 30.0 | 60.0 | 120.0 | 240.0 |
|------------|-----|-----|-----|-----|-----|------|------|------|-------|-------|
| Moisture content |    |     |     |     |     |      |      |      |       |       |
| %           | 60.13 | -   | -   | 52.25 | 50.72 | 49.68 |    | 46.74 | 43.79 |
| Shortening | 20.00 | 4.09 | 3.96 | 3.85 | 3.84% | 3.83% | 3.84% | 3.84% | 3.85% | 3.89% |
Considering the literature, dimensional change is not possible over FSP due to drying, thus, purely spring-back effect and stress relaxation can be the reason of both increase and decrease in length. As it can be seen in table 1, the average length of the 20 samples increased in the first 3 minutes after the compression forces had ceased. The initial compression ratio was 20% compared to the original length of the samples then the compression forces ceased, and the samples regained most of their original length in the first few seconds. There was a constant period in the length of the samples between 3 and 120 minutes after which their length started to decrease (Figure 3a).

Looking at both table 1 and figure 3a it is evident that the mass loss is the most intensive in the first short period. Performing a temperature check showed that the samples were approaching the laboratory temperature in about 20 minutes (Figure 3b). During this period, the mass loss is also more intense which means the loss of MC due to the strong evaporation. The top layers of the wood are in contact with the surrounding air. The MC will be here more rapidly reduced, after that the water loss slows down, but still remains significant. Following this natural process, artificial wood drying has to be done using increasing temperature and/or decreasing RH, as it has been described earlier.

Using the right scales, the time-mass change graphs and the time-length change graphs follow each other. This predicts a relationship between MC and the sizes of the samples. Two hours after pleating the length of the samples started to decrease despite their MC were highly over their FSP (Figure 3a). If we accept the literature value that the FSP of oak is 24.5%, a 0.4% length reduction can be found during 22% water loss over the FSP. Below FSP the shrinkage was 1.18%, a huge value compared to the shrinkage of the untreated samples. In the study of Báder and Németh [6] the total shrinkage of pleated oak wood was determined to be 0.68%. The difference can be because this time we used freshly treated samples, and expectedly after drying to 0% MC the subsequent shrinkage will be less, as previously demonstrated. The shrinkage over FSP can be a result of the buckling of cell walls, leading to the formation of micro-cracks. Buckling causes possibly the growth of the cell wall surface and the formation of new available chemical linking points. These assumptions, of course, require further experiments.

Based on our laboratory observation, if a pleated sample is bent and straightened several times in its moist and warm state, its length initially set will increase. This should be an effect of the buckled cell walls, which are straightened as a result of the bending of the sample.

4. Conclusions

This study determines the spring-back as well as the maximal shrinkage of longitudinally compressed Sessile oak, using 20% compression ratio compared to the original length of the samples and fixation for 1 minute. As a result of longitudinal compression or pleating, the cell walls of wood deform in a plisse-shade wavy manner.

The samples were prepared using green wood, thus, the initial moisture content was 60% before treatment. Despite of wood changes its properties below its fiber-saturation point, the samples shrink in their longitudinal direction over their entire humidity range. The original purpose of the study was
to observe the spring-back of the longitudinally compressed wood. Most of the spring-back occurred immediately after releasing the pressure, followed by a further minor spring-back within 3 minutes. The remaining shortening was averagely 3.84%, which, together with drying shrinkage, increased to a total of 5.50%. The high spring-back of compressed wood is the result of internal stresses, while the high shrinkage is also caused by the treatment. The cell walls of wood deform and consequently, they shrink differently: a part of the much higher lateral shrinkage appear in the longitudinal direction of the pleated wood.

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