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Proof of the Elongation Reserve of Longitudinally Compressed Wood by Tensile Tests

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Abstract

This paper deals with the proof of the theory of elongation reserve remaining in wood after compression parallel to the grain. After compression, the wood becomes much more pliable and the force required for bending is reduced. At the end of the 1-minute fixation following 20% compression, the compressive stress in the beech samples was reduced to an average of 72.3%, while the oak samples showed a 65.6% change. The remaining shortening at this time was 3-5%. At the end of the 3-hours fixation, the compressive stress had decreased to 37.1% for beech and 27.9% for oak, resulting in a residual shortening of 12-18%. An average maximum tensile force of 1.76 kN was required for untreated beech samples, which resulted in a 1.55 mm increase in size parallel to the grain. For specimens fixated for a short-time, a tensile force of 1.06 kN caused a 3.66 mm increase in size, while for specimens fixated for a long-time, a force of 0.85 kN caused an 8.79 mm increase in size. The trends were similar for oaks. The higher moisture content provided a significantly larger increase in size during the tensile tests. The existence of the elongation reserve was clearly confirmed.

Keywords*: wood compression parallel to the grain, compressive stress, tensile strength, tensile test, elongation reserve.*

1. Introduction

1.1. The anatomical structure of wood

Wood, as a natural composite, has been an important raw material for mankind since ancient times. It consists of three main components, cellulose, lignin and hemicelluloses. Before moving on to wood compression along the grain (pleating), it is important to clarify the general structure and cell structure of wood. Cells are usually made up of several cell walls; the outer wall is called the primary cell wall, while the subsequent layer is usually called the secondary cell wall, however, it is three-layered, they are distinguished by separate symbols (S1, S2, S3) (**Figure 1**).

The structure of the cells is very important from a mechanical point of view since strength is a determining factor in the fields of use of wood. The cells have an elongated structure; the cells that ensure the strength of wood are called fibers. In terms of the structure of the trunk, two large groups can be distinguished: heartwood and sapwood. The heartwood is an internal part of the trunk and does not play a role in active physiological processes. Its extractive material content is typically extremely high compared to sapwood, and the heartwood provides the appropriate strength. However, living cells are also needed around the inactive cells, which ensure the biological life of the tree. This function is performed by the sapwood, in which the vessels and tracheids serve as water and nutrient transport channels. However, it is important to mention that their structure has been discussed in general so far. The properties differ from tree to tree, but tree species can be grouped in several ways. Good examples of these are the marked differences between the hardwood groups of the ring-porous and the diffuse-porous. Thanks to these differences, the wood species can be used in several sectors. Nowadays, wood modification is widely researched and used for a variety of purposes. Its purpose is to improve the properties of certain wood species and increase their range of use.

1.2. Assuming the existence of the elongation reserve

As a result of the treatment, pleating results in a permanent shortening of the wood. Several changes take place in the wood during the compression, and accordingly, several theories have come to light to explain the significantly improved pliability. The primary theory is that during pleating, a reserve of elongation is created in the wood by the buckling of the cell walls. In other words, the buckled cell walls are able to straighten later (first appearances: [2, 3]). This is important because the failure of the wood during bending typically occurs in the tension zone (disruption), due to its low elasticity. The aim of this research is to prove or disprove, based on the measured results and their analysis, whether there really is an elongation reserve in the wood after pleating.

1.3. The history of compression

We distinguish two large groups in terms of compressing. Compression can be done parallel to the grain or perpendicular to the grain (Figure 2). The difference between the anatomical directions is also reflected in the goals of the modifications. With compression parallel to the grain, the material will be much more flexible, while with compression perpendicular to the grain, we can increase the density, thereby making the wood much harder.

The bending of wood as a process was already used in ancient Egypt. At that time, wood was only steamed, which softened the material and made it bendable. This made it possible to change the shape more easily without breaking the material. Once set to the correct shape, cooling and drying were used to finalize the change with minimal spring-back. The method is still popularly used today, however, the steaming process is very complicated and only economical in large-scale industrial series production. Nevertheless, softening methods have also been developed, as Kollman [4] mentions in his study. There are cooking methods where the wood is treated in alum or in anhydrous liquid ammonia.

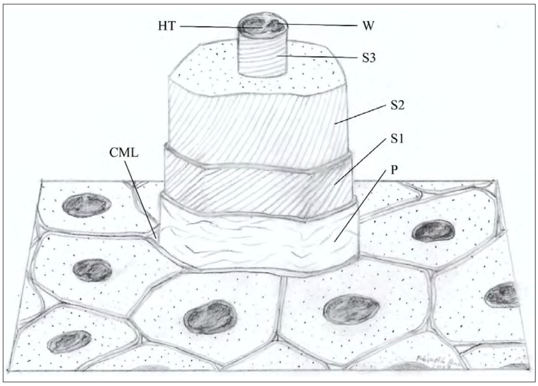

Figure 1. *Structure of the cell wall. (source: [1])*

1.4. The development of the pleating

This process was first introduced in the German Empire in 1917, which made it possible to bend wood at room temperature [5]. The method made it easier to bend the wood without much force, and had the advantage that the compressed material did not need to be reheated to achieve a high degree of bendability. An important part of the process was cooking or steaming before pleating, which softened the fibers enough to allow pleating without ruining the material. The pleated wood can be bent at any temperature. After the modification, the pleated wood was cooled, thanks to which it became further processable and could be cut into boards and other timber. Regarding the applied procedure, it can be stated that in this case it is a thermo-hydromechanical modification.

In 1917, an another patent was published in the German Empire, which further developed the previous patent for large-scale production [6]. In this development, the fixing time (the period during which the compressed wood is held in a compressed state) was to be triggered by means of a clamping device. Normally, after pressing, the material is left to fix inside the machine, which further strengthens the changes in properties caused by compression, but in this case the machine cannot be used for further compression.

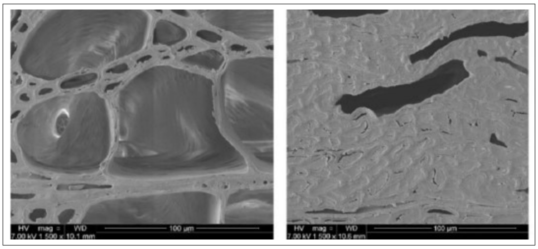

Figure 2. *Microscopic image of beech wood before and after perpendicular compression to the grain direction (source: [3])*

With the help of the developed device, the material could be taken out of the machine in a fixed state, ensuring permanent fixation, and then cooled. Meanwhile, the machine could already start compressing the next piece of wood. Unfortunately, the operation was so complex that the technology and production processes of the time did not allow its spread in the wood industry. This type was further developed in 1926 [7]. Holzveredelung GmbH created a machine based on Hanemann's preliminary patents, and it could already be successfully integrated into the industrial processes of the time and production became realistically feasible. An internal insert was developed, thanks to which the wood could be taken out of the machine immediately after pressing and kept it in a fixated state. In the meantime, it was already possible to refill the compression device with the new wood (**Figure 3**). In the decades that have passed since then, experts have initiated and implemented numerous developments, so that since the 1990s, PLC-controlled compression equipment has been available.

Pleating has been possible at the University of Sopron since 2015. Measurements and compression force are provided by an Instron 4208 universal material testing machine (Instron Corporation, USA). The compression process itself takes place in a machine unit specially developed for this purpose, which is described in subsection 2.2. The machine provides the possibility to compress 20×20×200 and 20×30×200 mm specimens pleating. Its maximum compression capability allows the tested material to be compressed to a ratio up to 33% smaller than its original length in the grain direction. Heating is built into the side walls ensuring the right temperature, and the side plates can move together with the wood being compressed in order to achieve the right compression ratio [8, 9].

The great advantage of pleating wood is that it is very economical in terms of raw material use. Curved furniture elements are mostly made of glued or glued-laminated elements, which require a lot of glue and wood. On the other hand, wood compressed along the grain provides a cost-effective solution.

Pleated wood is extremely versatile in terms of areas of application. As already mentioned, it can be perfectly used for creating curved furniture elements, as well as for vibration-damped tool handles, curved picture frames, car interior coverings, sports equipment, in the toy industry and musical instruments [3, 4, 10].

For pleated wood, production oversizing can be avoided, since even the finished form can be bent without breaking, in addition to all this, the direction of the grain follows the shape throughout, there are no fibers running out to the side. However, the disadvantage of the process is that discoloration due to steaming has to be taken into account. Thus, it is necessary to choose where it should be used aesthetically.

1.5. Tömörítésre alkalmas fafajok

Based on preliminary studies and research, it can be stated that a wide range of wood species can be used for compression. There is a large selection of hardwood species, most of them are especially suitable for compression, for example beech (*Fagus sylvatica* v. *Fagus* ssp.), oak (*Quercus* ssp., *Quercus petraea*, *Quercus velutina*), black cherry (*Prumus serotina*), ash (*Fraximus excelsior*, *Fraximus americana*), and silver maple (*Acer saccharinum*) and pear wood, too [4]. Differences can be read in various literature when we are interested in robinia, poplar or linden. The compression properties of these wood species are doubtful.

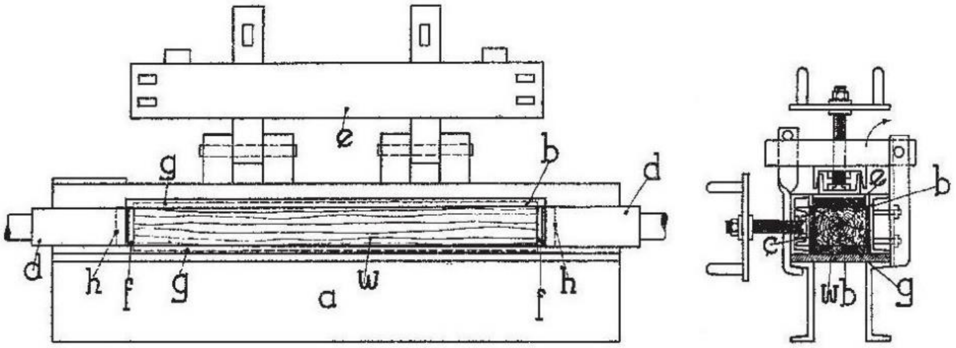

Figure 3. *The first compressing machine produced for industrial use. (source:* [7]*)*

In order for the wood to be pleated without problems, special attention must be paid to the quality of the material to be used. Only the knot-free, narrow annual-ring wood of a straight-growing tree can be used for compression. The direction of the fibers of the material must be parallel to the longitudinal edges of the workpiece, which means that a maximum deviation of 7° can be accepted. The quality of the material itself is much more important for compression than the method by which it was cut from the log, in this case this aspect is negligible information **[11]**. For wood prone to false grain, special attention must be paid to the fact that the wood to be used must not contain false heartwood, as it has different mechanical properties and would impair the final result. From the point of view of knots, large knots are to be avoided, however, pin knots are allowed on the surface, but these are not very desirable either, since these points absorb the greatest stress, which means that in the case of tensile tests, possible failure will take place on these weakened cross-sections. When designing the specimens, it is also important to take into account the shape factor, because the cross-section of the material changes as a result of steaming and cooking. This is due to changes in moisture content. It is also possible to compress bundled specimens. However, it is important that only one wood species can be compressed in a bundle, and their placement in the machine is only possible if they behave as one material.

In the cellular structure of wood, we distinguish between two types of water, free water and bound water. The free water is found inside the cells, in the cell lumina, while the bound water tends to settle on the walls of the cells. Fiber saturation point (FSP) is the state when there is no free water in the cell lumina, but the bound water accumulates in the largest possible amount on the walls of the cells. The fiber saturation point is different for each wood species, for beech it is 35.6%, while for oak it is 24.5% **[12]**. If we average the different FSPs of the wood species, we would get roughly 30%. Thanks to this value, it is also used in practice for large amounts of wood. For compression, mostly green wood is suitable, but with a moisture content of at least 16% **[13]**. . According to other literature, the moisture content of the wood suitable for compression is 2-8% less than the *FSP* **[14]**.

2. Materials and methods, description of technology processes

2.1. Fiber softening process

The modification process consists of three important parts: fiber softening, compression itself and post-treatments. Thanks to the hollow cell structure of the wood, compression can be carried out non-destructively, however, since the untreated material is very stiff, it must always be steamed/cooked beforehand in order to make it easier to form and to soften the fibers. From a chemical point of view, hemicelluloses and lignin change under the influence of the right amount of heat and moisture, which allows the mechanical properties of wood to decrease, like the modulus of elasticity. The cellulose fibers form a rigid structure in the cell wall, however, under the influence of heat and moisture, the matrix material consisting mainly of lignin and hemicelluloses softens **[15]**, and the cells can slide over each other during compression and bending. During steaming, wood begins to decompose at approximately 100 °C. Initially, damage to the hemicelluloses is observed, due to which the resistance of the wood to pressure decreases, in other words this condition is particularly advantageous for compression in the direction of the grain. According to specialist literature, the reference value for overheating of wood is 2 min/mm **[16, 17]**, taking this value into account, the appropriate steaming time must be defined depending on the cross-section to be compressed.

Overall, it can be stated that before compression, the wood must always be steamed at a temperature between 80-100 °C for better pliability, so that the level of fiber softening will be adequate to start compression (**Figure 4**).

Figure 4. *The vessel used for steaming the specimens.*

2.2. Application of Instron 4208 material testing machine for pleating

As previously mentioned, fiber compression has been possible at the University of Sopron since 2015. In order to apply the technology, a machine (Instron 4208) capable of exerting a suitable amount of force was needed, as well as a compression unit that could be connected to the machine (**Figure 5**).

The construction of the compression unit is simple and performs its function perfectly. It consists of two main parts. From a rigid-walled compression chamber, the inner side walls of which can move with the compressed material, and from a heated outer side wall, which ensures the right temperature for the duration of compression (**Figure 6**).

The settings of the compression program were suitable for all specimens, we only changed one parameter, the fixation time. The size of the fixation time largely determines the degree of change in the material properties, the longer the fixation time causes a greater permanent shortening and, with this, the elongation reserve probably also increases.

In the course of the research, we examined two tree species, beech (*Fagus sylvatica*) and sessile oak (*Quercus petraea*), and two fixation times were used for each tree species, a fixation time of one minute (fixated for a short time) and 3 hours (fixated for a long time), respectively. According to this, we could separate four groups of compressed specimens in addition to the untreated ones.

2.3. Pleating

Once the fiber softening process is complete, the pleating can begin. The object to be compressed is placed in the compression chamber, where the specimens are using high pressure, in which case a size reduction of up to 33% can be achieved without destroying the material. It is important to mention that the maximum compression value of 33% is determined by the laboratory compression equipment we use. Every type of wood has a compressibility limit, beyond which the material undergoes substantial structural destruction, so it breaks down and will not be suitable for casting. Based on previous, unpublished research, for example, the highest compressibility ratio before failure in oak is 21-23%, while in the case of beech it can reach up to 30%. During our tests, the compression was carried out with a 20% decrease in size in the fiber direction for all specimen groups, thereby guaranteeing adequate compression without significant structural damage. The relative compression rate was 25%/min **[1]**.

When the appropriate pressing ratio is reached, fixation can begin, where its internal stresses de-

Figure 5. *Compression unit close up.*

Figure 6. *The internal structure of compression unit.*

crease and its permanent shortening and bendability increase. It is important to mention that the longer the fixing is done, the less the material will bounce back.

2.4. Post-treatment of pleated wood

Once the test pieces are removed from the compression chamber, post-treatment processes can begin. Since it has to be steamed before compression, it has a high moisture content after the process is finished, so the next step is the drying, as a post-treatment. Several methods can be used for drying, the choice of which depends on the specific area of use of wood. However, it is important to mention that the flexibility of the wood deteriorates rapidly during drying. At a moisture content of 0-5%, it often happens that wood compressed in the grain direction is more brittle than untreated wood. Overall, it can be concluded that drying, as a post-treatment process, serves as a final operation. The compressed material is bent into the desired shape, and then this change in shape is finalized by drying. However, it is important that the bent material must be dried attached to the bending template, so that there will certainly be no deviations in shape after the process is finished. Previous studies have shown [9], that the bendability of pleated wood is greatest when it is close to fiber saturation point.

The bendability of the compressed material can be preserved, but this requires a suitable moisture content. This means that, subject to the appropriate climatic conditions, it is not important to use the pleated wood immediately, but it can be perfectly stored, thus facilitating the mass production of factories with a large consumption of material.

2.5. The process of forming the tensile samples

During the process, we compressed 20×30×200 mm specimens (**Figure 7**), but they were still too large to be subjected to tensile tests.

Each large specimen was sliced into small test specimens 2 mm thick (2×20×160–200 mm depending on the treatment), it was usually possible to create 4 small samples from one large specimen, also taking into account the width of the cutting gap (**Figure 8**).

The sliced samples were routed to a standardized profile using a plunge router machine, which were already suitable for carrying out the tensile tests (**Figure 9**). The tested part was 2×8×50 mm for each tensile sample.

Figure 7. *20×30×200 mm beech specimen.*

Figure 8. *Thin specimens cut from larger beech specimens in order of compressed and fixated for a long time, fixated for a short time and untreated.*

Figure 9. *Fixated for a long time, fixated for a short time and untreated small samples in sequence, with a profile designed for tensile testing.*

In **Figure 8** the specimen on the left is clearly curved, so the profile was designed in line with the original shape. During the three-hour fixated pleating, most of the large specimens were bent after being removed from the compression equipment. As we mentioned also in subsection 1.5, it is important that all fibers are located parallel in the specimen, in order to preserve parallelism, the design of the tensile sample must be adjusted to the curvature of the material, so there will be no fiber run-out, which can lead to incorrect measurements in the tensile test.

For both beech and oak, a total of three specimen groups were created. We examined the mechanical properties of wood specimens fixated for a long time, fixated for a short time and untreated. The three main specimen groups underwent different pre-treatments, the purpose of which was to be able to carry out a wider range of tests.

During the first type of pre-treatment, the samples were conditioned to a moisture content of 12% at a temperature of 20 °C at a humidity of 65% (normal conditions). In the second type of pre-treatment, the samples were first dried to 0% moisture content and then climatized under normal conditions. In the third type of pre-treatment, the samples were stored in wet state close to green moisture content, which was achieved by freezing so that the water formed solid molecules in the wood, thereby disabling evaporation and the appearance of biotic pesticides. We examined an average of 40 tensile samples per specimen group, in other words the data of a total of 240 samples were processed.

2.6. Tensile tests

After the design of the samples and the compilation of the specimen groups was completed, the specimens were subjected to tensile tests. We used a Tinius Olsen H10KT (Tinius Olsen Ltd. Redhill, England) material testing machine to carry out the tests. The lower grip has a fixed position, while the upper grip can move in the direction of the „z” coordinate (**Figure 10**).

Since the strength and elongation of the fixated for a long time, fixated for a short time and untreated specimens were significantly different, we chose a different tension rate for each group of specimens. Our aim was for all samples to fail in a uniform time interval as defined by the associated test standards (ISO 13061-6:2014 [18]) Considering the failure times, the correct rate was 3 mm/s for untreated samples, 4 mm/s for fixated for a short time samples, and 8 mm/s for fixated for a long time samples.

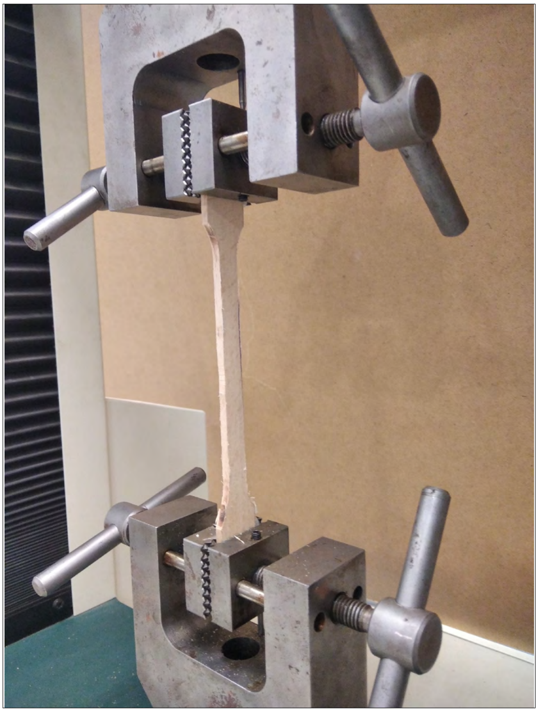

Figure 10. *Clamping a tensile sample into the material testing machine.*

3. Results and evaluation

3.1. The changes in compressive stress due to fixation

During compression along the grain, wood is in plasticized state, thus preventing its destruction. Achieving a compression ratio of 20% requires significant force, which all of our samples withstood without damage. In the moment when the compression ratio of 20% was reached, the actual compression force divided by the cross-section gave the highest compression stress. Keeping the 20% compression ratio at a constant value (fixation), the compression stress initially quickly decreases and then the decrease gradually slows, as is typical for the stress relaxation of viscoelastic materials.

The beech and oak specimens reacted differently to the compression. As shown in **Figure 11** after 20% compression, the compressive stress of the beech specimens decreased to 72.3% after 1 minute of fixation, while the same was 65.6% for the oak specimens. Long fixation (compressed for 3 hours) reduced the compressive stress to 37.1% for beech and 27.9% for oak. It should be noted that the significant difference is also a consequence of cooling to room temperature. At the same time, the structure of the specimens changed significantly as a result of both compression and fixation for a long time, as has already been demonstrated by numerous microscopic analyses [9]. Analyzing the permanent shortening values, it can be said that in all cases the oaks suffered a greater permanent deformation than the beeches. After 20% compression and short fixation, the shape change was 3-5%, while long-term fixation resulted in a permanent shortening of the specimens of 12-18%. These are very significant changes, which are coupled with serious changes of the anatomical-physical-mechanical properties. This is reported in **Figure 11**, which shows both the averages of the maximum compressive stresses and the averages of the compressive stresses measured at the end of the fixations. In general, it can be said that a third of the compressive stress created during compression is removed during one-minute fixation, while a three-hour fixation reduces the compressive stress significantly more, by two-thirds.

3.2. Relationships between the degree of rebound and the magnitude of the exerted force

For specimens conditioned to 12% moisture content at 20 °C temperature and 65% relative humidity (normal condition), it can be observed for both wood species that the tensile forces are opposite to the size changes along the grain, as can be seen in **Figures 12.** and **13.** The tensile force applied to the untreated beech samples was 1.76 kN on average until the moment of rupture with an average increase in length along the grain of 1.55 mm. For the samples fixated for a short time a smaller force was required, on average 1.06 kN, to achieve an average 3.66 mm increase in length in the fiber direction, however, the most spectacular results were obtained for the samples fixated for a long time. An average force of just 0.85 kN was enough to increase the length by averagely 8.79 mm. This means that the magnitude of the tensile force changes opposite to the fixation time for a given amount of elongation. For specimens fixated for a long time, which were under continuous pressure for 3 hours, we can achieve greater increase in fiber direction with much less force. This finding was also true for all other samples during the measurements.

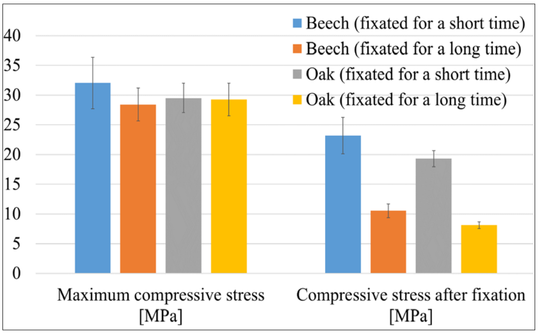

Figure 11. *Compressive stresses after pleating and after different times of fixation.*

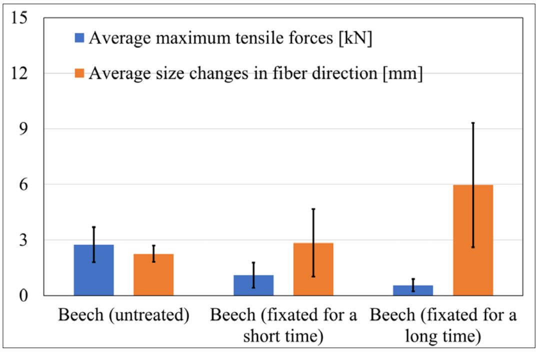

Figure 12. *Correlations of tensile tests of beech wood.*

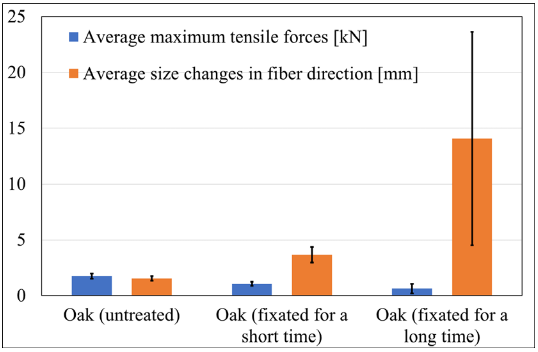

Figure 13. *Correlations of tensile tests of oak wood.*

3.3. Dimension changes depending on the fixation time

For both tree species, the length of the specimens differs depending on the treatment (untreated, fixated for a short time and fixated for a long time groups). It can be perfectly demonstrated that fixation for a long time is the most effective procedure in terms of the ability to change the size in the grain direction, as can be seen in **Figures 14.** and **15.** This is in line with the finding of Báder and Németh **[19]** according to the deflection of the compressed samples by 20% during a 4-point bending test: these samples have 3-4 times higher pliability compared to the untreated ones, while the fixated for a long time can withstand at least a six-fold deflection.

3.4. The influence of moisture content on the dimension changes during the tensile tests

Figures 16 and **17** summarize the averages of the dimension changes parallel to the grain for all three sample groups and for both wood species. It is perfectly visible that in almost all cases the samples with the highest moisture content had the largest deformation during the tensile tests. This finding also supports the results of previous research **[9]**, that the bendability/elongability of wood is greatest when it is in a state close to fiber saturation point. The other sample groups contained much less water than these sample groups, so it was closest to the fiber saturation point.

3.5. Relationship of specimen groups close to the green state

Interestingly, a lot of similarities can be observed between the length change along the fibers - tensile force graphs of both wood species in **Figures 18** and **19.** The graphs of the untreated specimens slope sharply upwards, thus, a large force is necessary to achieve a small length change. For the specimens fixated for a short time significantly less force is needed for the same length change along the fibers and the maximum length change is greater, compared to the untreated specimens. Finally, the graphs of the specimens fixated for a long time show the most spectacular deviation, since here, thanks to the large-scale changes in cell structure **[19]** the largest maximum length change can be achieved with relatively low maximum force compared to the untreated specimens.

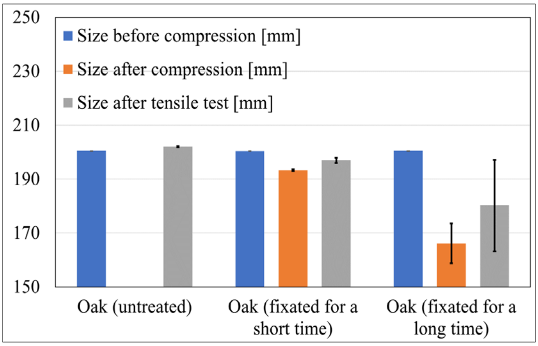

Figure 14. *Average size of oak samples parallel to the fibers in the different phases of the test.*

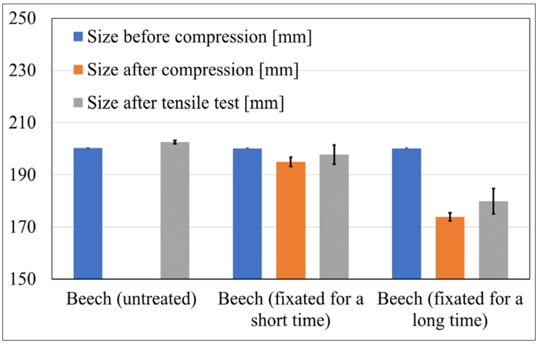

Figure 15. *Average size of beech samples parallel to the fibers in the different phases of the test.*

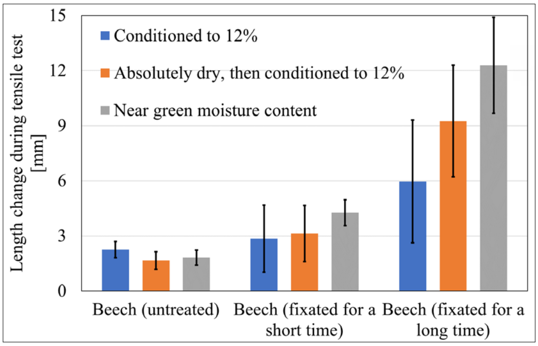

Figure 16. *Average length change of beech samples during tensile tests at different moisture contents.*

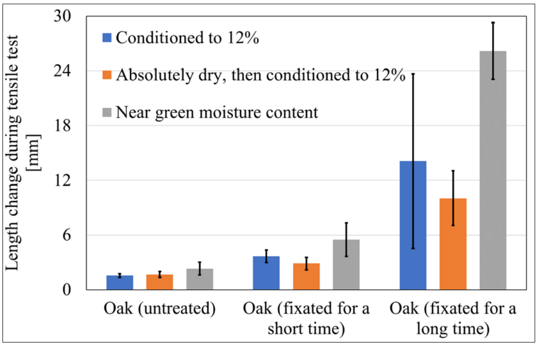

Figure 17. *Average length change of oak samples during tensile tests at different moisture contents.*

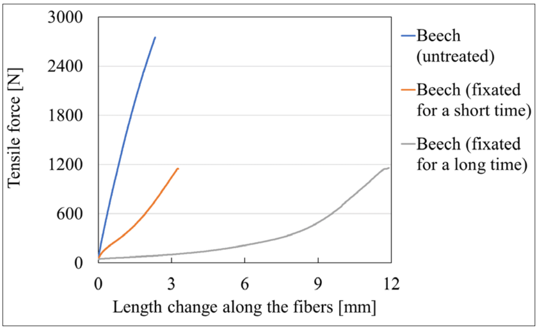

Figure 18. *Force - length change graphs for representative specimens of all three beech sample groups with near green moisture content.*

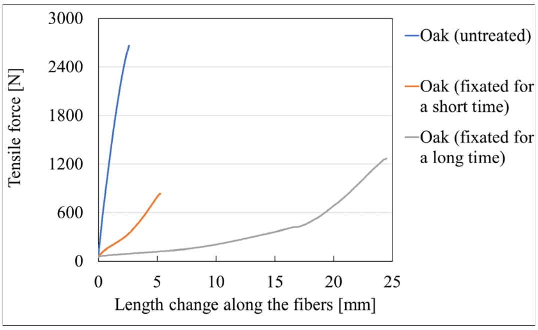

Figure 19. *Force - length change graphs for representative specimens of all three oak sample groups with near green moisture content.*

4. Conclusions

The aim of the study is to prove the theory of the elongation reserve of the pleated wood, as well as to examine and compare the mechanical effects of the various changes in material structure associated with the modification process with the mechanical properties of untreated wood.

The data and diagrams illustrated above serve as proof of the existence of the elongation reserve. The knowledge of this can serve as an important factor in further research on pleating, as well as in the application of pleated wood in the furniture industry, where curved elements can be made. By taking into account the elongation reserve, the change in dimensions and flexibility of the compressed material can be calculated more precisely, which will facilitate the production of curved elements in the future.

During the tests, we not only found evidence for the existence of the elongation reserve, but also found a clear explanation for the findings of previous tests: the significant increase in the pliability of wood compressed along the grain is the result of the improvement of the ability to increase in size along the grain. In addition, we proved that the ability of the specimens to increase in size along the grain is significantly higher at a moisture content close to the fiber saturation point than at a moisture content of 12%.

In the future, we will expand the number of tested sample groups, which will be subjected to other pre-treatments before the tensile tests, such samples with a moisture content of 20-25% and samples dried artificially.

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