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THE EFFECT OF THE RELAXATION TIME ON THE MECHANICAL PROPERTIES OF LONGITUDINALLY COMPRESSED WOOD

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ABSTRACT

Longitudinal compression makes natural wood easier to bend. The relaxation after compression results in much improved bending properties. During a bending test, the maximum deflection increases with the relaxation time, while the needed force to reach the same deflection decreases, similarly to the modulus of elasticity (*MoE*). The modulus of rupture (*MoR*) of the compressed wood does not change considerably compared to the untreated wood, except at the long-time relaxed samples. The ideal relaxation time is 1 minute. After that the change of the important properties slows down. Of course with special demands, the relaxation time can be also very long. In this case the process leads to a wood sample with pronounced flexible properties. Samples were left to rest between normal circumstances for 1 day, but this resting period did not have a significant effect on its mechanical properties.

KEYWORDS: Wood modification, pleating, wood bending, ductility, memory effect, springback.

INTRODUCTION

The longitudinal compression results in easily bendable wood. The traditional system of steam bending also has a similar effect but the wood can only be bent while it is hot and wet. Moreover, the wood will bend more easily and in smaller curves by longitudinal compression, even when it is cold (Sandberg and Navi 2007). Therefore, the longitudinally compressed wood 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. Disturbing lines of joints on the surfaces of the product can be avoided, because many parts can be made of one piece of modified wood (Sparke 1989). Conventional tools can be used both for processing (sawing, planing, sanding, etc.) and bending (Conradsson 2007).

After drying, longitudinally compressed wood preserves its new shape, as the deformations are frozen (Heisel 1990, Buchter et al. 1993).

Due to this modification, the required bending force and the *MoE* decrease dramatically, ensuring a high deformability (Kuzsella 2011). These property changes of the wood can be explained by the cell wall deformations (Sandberg and Navi 2007). The compression and also the bending requires high quality hardwood raw material (narrow annual rings, defect free, straight grained) (Szabó 2002). Before the compression procedure, the wood has to be plasticized (Ivánovics 2006). Earlier laboratory investigations have proven that in order to avoid the unwanted damage of wood during compression, the moisture content must be kept above the fibre saturation point. Otherwise during steaming the moisture content would increase, the sample would swell and twist, and it might be inadequate for the modification process (Báder and Németh 2017). The compressed sample is wet, and remains easily bendable until the moisture content is high (Báder 2015). It is important to have an equal compression ratio along the entire length to provide homogeneous mechanical properties in each sample. Earlier investigations on a laboratory scale (Báder and Németh 2017) showed that unequal compression ratios along the length of the sample occur very rarely in only about 2% of the samples. Samples showing unequal compression cracked in most cases.

Many patents deal with the longitudinal compression. The patent of Hanemann (1917) in Germany was published 75 years after the first patent of Michael Thonet. This was an alternative to Thonet's technology, upgrading the properties of the product. Schneider (1939) mentioned longitudinally compressed wood in his book on aircraft and aircraft parts as a raw material purchase and utilization option. In Vorreiter (1949), Kollmann (1951), Kuzsella (2011), the characterization of longitudinally compressed wood is discussed. Nowadays, modern compressing machines working around the world e.g. in Hungary, Italy and the USA. The products are mostly used in furniture industry: chairs and skirting, or furniture rim, mattress coil springs, etc. It can be used in interior design as wooden handrails, coat hooks, and applied arts, etc. (Báder 2015). Other applications are also possible, e.g. vibration dampening tool shafts, car panels, wood toys, medical aids, etc. (Báder 2015). In areas where corners are not allowed, excellent raw material for product design, for example, ship and aircraft furniture (Vorreiter 1949, Báder 2015). Outdoor use is less frequent, because the material weathers and can re-moisten (Vorreiter 1949, Conradsson 2007).

There are also scientific publications and academic theses which are specifically concerned with the properties and use of compressed wood (Vorreiter 1949, Buchter et al. 1993, Anssary 2006, Ivánovics 2006, Hyams 2008, Kuzsella 2011, Peres et al. 2013, Dienes 2013, etc.). Different sources present different results related to the modulus of rupture (*MoR*) and the modulus of elasticity (*MoE*) of the longitudinally compressed wood (Báder 2015). In the Tab. 1 the changes of these properties can be seen due to the longitudinal compression. The source articles do not reveal the conditions of the wood or the details of the research, so it is hard to compare their results. The data in the Tab. 1 vary in a wide range, but the tendency seems to be evident. As a result of the longitudinal compression, both the *MoR* and the *MoE* decrease, especially the *MoE*.

Tab. 1: Change of the modulus of rupture (MoR) and the modulus of elasticity (MoE) due to the 20% longitudinal compression (based on Báder 2015).

Author	MoR		MoE	
	(%)	(%)	(%)	(%)
	Beech	Oak	Beech	Oak
Buchter et al. (1993)	-10.0		-15.0	
Ivánovics (2006)	-45.8	-42.1	-68.1	-60.0
Kuzsella and Szabó (2006)	-47.2	-16.8	-69.5	-45.4
Candidus (2014)	-27.5		-64.5	

The aim of this study is to determine the changes of some physical and mechanical properties (compression stress, remaining shortening, *MoR, MoE*, etc.) of oak wood due to longitudinal compression by 20%, as well as the determination of the optimal time of holding the sample in a compressed state and its effects on the material. It is also important to reveal the correlations between the physical and mechanical changes of this modified material.

MATERIALS AND METHODS

Longitudinal compression and relaxation

The raw material was Sessile oak (*Quercus petraea* (Matt.) Liebl.), from the Sopron region, Hungary. The dimensions of the samples were 20×20×200 mm (radial × tangential × longitudinal), determined by the laboratory-scale compressing machine. For longitudinal compression defect-free, precisely sized hardwood was used, with high moisture content and minimal fiber slope, cut from a straight grown tree (Báder and Németh 2016).

Longitudinal compression is a thermo-hydro-mechanical modification process. During the modification process at least 80°C temperature should be maintained throughout the entire cross section of the material, to be able to compress the sample without breaks and cracks. In this experiment, we used steaming at atmospheric pressure. After steaming, the samples were longitudinally compressed at 90°C to 100°C degrees. Longitudinal compression can be achieved as the workpiece is kept straight during the compression process, through supports on the sides. The lateral distance and the clamping force between the opposing side walls can be individually set in the compression machine for each sample. Using the same lateral clamping force throughout the whole length, it is possible to avoid an increase in cross-sectional size and to keep the sample straight. This is a semi-closed, unique laboratory equipment which allows minimal contact with the air for the sample. The device is self-engineered and individually produced, and developed to operate in an Instron 4208 (Instron Corporation, USA) universal material testing machine. The properties of longitudinally compressed wood can be influenced through setting the compression ratio (Báder 2015). All samples were compressed by 20% compared to their original lengths, at a rate of 30 $mm \cdot min^{-1}$. After compression, the sample can be held for a while compressed, this period is called relaxation. During relaxation, the compression ratio is kept constant. Relaxation time can be set in the test program of the Instron material testing machine. Tab. 2 shows the test methods and the sample numbers in the recent experiment.

Tab. 2: Test methods and naming of oak samples.

Marking	Pieces	Sample marking explanation
OC	20	Control
OSC	20	Steamed Control
O0m	20	Compressed without relaxation
O1m	20	Compressed with 1 minute of relaxation
O3m	18	Compressed with 3 minutes of relaxation
O5m	4	Compressed with 5 minutes of relaxation
OLm	3	Compressed with a long-time relaxation (averagely 900 minutes)

In the relaxation phase the pressing force decreases quickly at first and then the decreasing gradually slows down but still goes on even after many hours as the sample cools down. In Fig. 1 the influence of 5 minutes of relaxation can be seen.

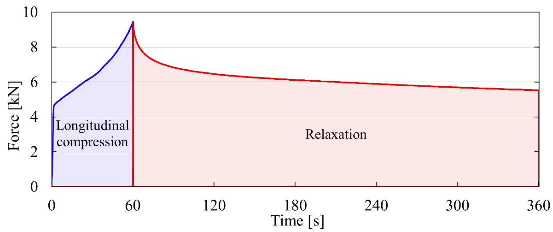

Fig. 1: A typical Time - Force graph of a longitudinal compression with a 5 minute relaxation.

All relaxations were made in the heated laboratory compression chamber. At the OLm samples the heating was switched off during the relaxation. In this case, the system with the sample cooled down, and thus the moisture loss was eliminated.

Every sample was analyzed visually to find cracks or other faults which might have happened during the wood modification. Only 2 cracked pieces of the 110 samples were found and these were eliminated from the next measurements.

After these treatments, the samples were dried at a temperature of 40°C for 48 hours, then conditioned at 20°C and 65% relative moisture (*RH*) until a constant weight was reached.

Resting

The longitudinal compression treatment is an intensive wood modification method which induces stresses in the wood due to its structural transformation. Relaxation eliminates many stresses (Báder and Németh 2017) but some samples deformed during the following drying process, showing residual stresses in the wood. We inserted a 24-hour resting period at 20°C and 65% *RH* normal conditions between the compression-relaxation process (compression rate 50 mm·min^{-1}, relaxation time 1 minute) and the drying process to let the wood reduce its internal stresses. The careful drying process started at a temperature of 25°C, and this temperature was increased to 30°C 7 days later. The temperatures of the intensive drying process increased from 45°C to 60°C in 7 days. The drying processes took 30 and 25 days, respectively, in the Binder KBF-115 climate chamber (Binder GmbH., Germany). The range of *RH* decreased between 80% and 45% for both processes. After drying, the samples were conditioned at 20°C and 65% *RH*. The same Sessile Oak raw material (*Quercus petraea* (Matt.) Liebl.) was used in the "resting" experiment as in the relaxation examinations, and Beech wood (*Fagus sylvatica* L.) was also used. There were 20 samples of each kind of material and treatment.

Bending test

Macromechanical experiments were made with longitudinally compressed wood both after relaxation and resting to get the discrepancies that different treatments initiate. After conditioning, 4 point bending tests were carried out.

The current European standard EN 408:2010 specifies an L=18±3h support-span/sample-thickness ratio (L/h). However, since the goal of longitudinal compression is high bendability, we had to use a smaller ratio to reach the failure point of the samples in order to measure their strength values. Because of the shorter samples, we had to change the originally quadratic cross sections to rectangular. The height of the samples (h) was cut back to 13.0 mm, while the width (b) was left the original size. This way after the re-conditioning we could provide the proper L/h ratio for the 4 point bending test (L/h=12.49±0.26 averagely for all samples). The position of annual rings was in a vertical direction during the bending examinations, so the different annual ring angles could not cause considerable deviations in the mechanical data. The bending test was made with a displacement driven at a rate of 8 mm·min^{-1} with the control and 16 mm·min^{-1} with the compressed samples. Tests were stopped upon failure, when the load dropped with no recovery. The *MoR* was determined by Eq. 1 according to the standard EN 408:2010.

$$MoR_u = \frac{3 \cdot F \cdot a}{b \cdot h^2} \tag{1}$$

where: MoR_u - the modulus of rupture at equilibrium moisture content,
F - the maximum load,
a - the distance between the loading span and the nearest support span.

The determination of the bending modulus of elasticity comes from the wood bending tests force-deflection data. In the natural wood samples, the elastic part of the curve belongs to the 10-40% of the maximum force according to the standard, but with the longitudinally compressed wood the elastic part of the curve is shorter, so we had to use the 10-25% range of the maximum force in order to remain in the linear range. The *MoE* was determined as described by Kossa (2013) (Eq. 2).

$$MoE_u = \frac{\Delta F \cdot a^2 \cdot (3 \cdot L - 4 \cdot a)}{12 \cdot I_x \cdot \Delta w} \tag{2}$$

where: MoE_u - the bending modulus of elasticity at equilibrium moisture content,
ΔF - the difference between the 10% and 25% of the maximum load,
L - the distance between support spans,
I_x - the second moment of area,
Δw - the increment of the load span displacement corresponding to ΔF.

The maximum deflection (y_{max}) of the 4 point bending test does not match the load span displacement, as at the 3 point bending test. The maximum deflection was also determined by Kossa (2013) (Eq. 3).

$$y_{max} = \frac{w \cdot (3 \cdot L^2 - 4 \cdot a^2)}{4 \cdot a \cdot (3 \cdot L - 4 \cdot a)} \tag{3}$$

where w is the maximum load span displacement.

Eq. 3 defines the deflection for samples with low bending ability in static bending tests. Since the longitudinally compressed wood samples have a high deflection, the amendment of Eq. 3 is needed. When measuring the real maximum deflections ($y_{max\ real}$), a linear supplemental equation was made (Eq. 4):

$$y_{max\ real} = 1{,}1563 \cdot y_{max} - 0{,}7345 \quad (4)$$

Between the real deflection and the calculation the statistical coefficient of correlation is R^2=0.9995. This way the original equation by Kossa (Eq. 3) has been applicable also for highly bendable wood materials.

Finally, the samples were analyzed visually, and their moisture content was determined by drying the samples to 0% moisture content in an oven at a temperature of 103°C. The moisture contents were 14.1±0.4% at the time of the bending examinations.

For the strength-strain graph of a bending test, the relative deformation (ϵ) is necessary. This means the change of the length. This dimensionless measurement of stretching was determined as described by Vorreiter (1949) (Eq. 5):

$$\epsilon = \frac{y \cdot 6 \cdot h}{L^2} \quad (5)$$

where y is the momentary deflection of the sample. During loading, the dimension changes in the cross section can be neglected.

Scanning electron microscopy

The scanning electron microscopy (*SEM*) imaging was made using a Hitachi S-3400N (Tokyo, Japan) microscope. Approx. 5×20 mm (T×L) sample surfaces were prepared using a sliding microtome, parallel to fiber direction. The samples were put in a high-vacuum of 6 kPa. The accelerating voltage of the electron beam was 10 kV, the emission current about 100 µA and the working distance was between 8 and 13 mm. The magnification was 300, 500 and 1000. Before imaging, automatic contrast, brightness and focus were made with a Hitachi software version 1.24. Later the contrast and the gamma of the images were optimized with IrfanView 4.38 freeware.

Statistical analysis

The statistical analysis was made using the Dell Statistica version 13 software. The sample numbers were adequate to make proper descriptive statistics for the box plot graphs. Statistical analysis of the differences of 1- the compression stress change and 2- the remaining length change compared with each other and 3- other measured properties was made using a T-test, and the variables were treated as dependent samples. The correlation coefficients (R) and the adjusted coefficients of determination ($R^2 adj.$) between the properties were calculated to determine their relationship with a regression summary for dependent variables. Comparative analyses of the results of the different treatments were determined by a one-way analysis of variance (ANOVA) Fischer LSD test with probabilities for post hoc tests. All differences were marked as significant at $p < 0.05000$.

RESULTS AND DISCUSSION

Fig. 2a shows scanning electron microscopy (*SEM*) images of the trachea (left) and the fibres (right) of control oak wood. All the lumen walls are smooth, and all other parts (wood rays, parenchyma, and pith) are intact. Fig. 2b shows a longitudinally compressed sample without relaxation. The trachea seems intact, while the fibre walls are definitely distorted.

Fig. 2c shows a longitudinally compressed and long-time relaxed sample. In this case both the walls of tracheas and fibres are highly distorted, and look like an accordion. As Stevens and Turner (1948) described, the cell walls buckle so as somewhat to resemble a half-closed concertina. The smaller fibre lumens and pit openings (e.g. on the walls of vessels) often fully disappear. During long-time relaxation, the wood cools down in a compressed state and the remaining deformations are more pronounced, because the wood keeps the deformations better. The cells can slip in some degree compared to each other, as claimed by many hypotheses (Sparke 1989, Deibl et al. 1999, Kuzsella 2011, Ivánovics 2012), by this loosen the distortions.

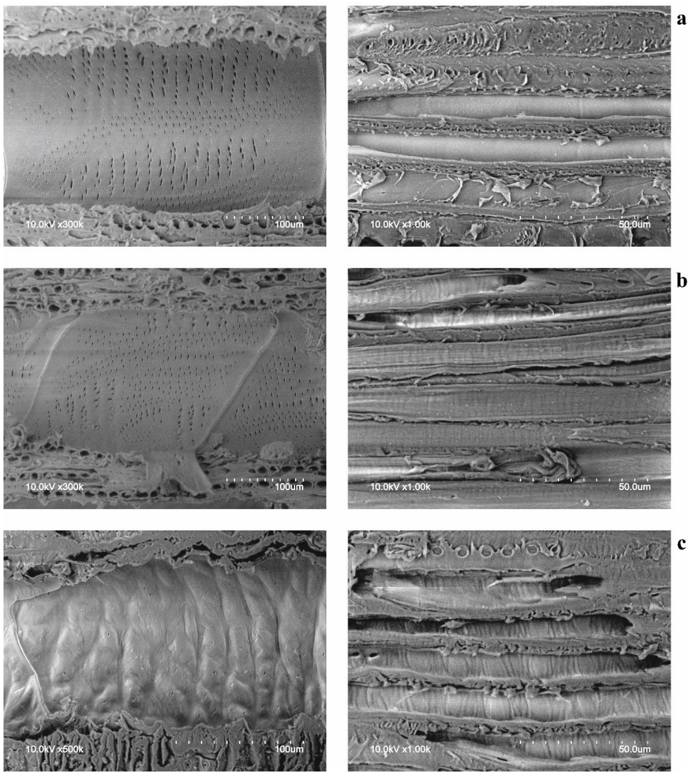

Fig. 2: Scanning electron microscopy images of the trachea (left; 10 kV x300 and x500) and the fibres (right; 10 kV x1000) of oak wood in a control sample (a), a longitudinally compressed sample without relaxation (b), and a longitudinally compressed sample with long-time relaxation (c).

Comparing the results, after longitudinal compression, the thick-wall fibers have significant remaining changes (Fig. 2b), while the cells with thin walls, for example tracheas more easily recover their original shape after the pressure load is removed. In longitudinal compression, the "springback" property of wood (also known as memory effect) causes this phenomenon. After a long-time relaxation treatment, every part of the wood suffer permanent changes. The remaining length change shows the same tendency (Fig. 3). With the increasing relaxation time the remaining shortening increases, i.e. the spring-back will be much weaker.

The longitudinal compression was also called "crushing" (Navi and Pizzi 2015), but the wood fibre does not break as the word "crushing" means. The structure and properties will be changed according to the expectations of the modification process and the wood remains useable. The reason for new properties of wood can be explained by cell wall deformations, that it distorts and seems like an accordion or a plisse shade on the microscopic images (Fig. 2c), and this way a more precise name for the phenomenon would be "accordionisation" or "pleating".

Mechanical properties

The *MoR* for the control samples averaged 110.4 MPa. In the literature, there are values of 78-110-117 MPa (Wagenführ 1996), 105.0 MPa (Kretschmann 2010), 97.1 MPa (Meier 2016), etc. The differences can be explained by the different sample dimensions, *L/h* ratios and the differences between the 3 and the 4 point bending tests.

For *MoE* of the control samples we got an average 10.0 GPa, while the literature gives 9.2-13.0-13.5 GPa (Wagenführ 1996), 12.3 GPa (Kretschmann 2010), 10.47 GPa (Meier 2016), etc. for oak wood. The reason for these differences can be found in the setup deviations between the 3 and the 4 point bending tests. All the results are shown in Fig. 3.

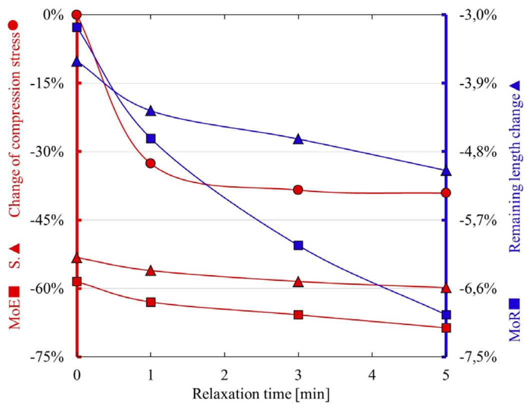

Fig. 3: Mechanical and physical properties after compression with the increasing relaxation time. Abbreviations: S.-Stress change at 5 mm load span displacement; MoE-change of modulus of elasticity; MoR-change of modulus of rupture.

The differences between the mechanical properties of control and steamed control samples are negligible so it is not necessary to discuss them separately.

The stress at 5 mm load span displacement shows us the first advantage of the pleating method. The stress needed for the 5 mm load span displacement was 100.0 MPa for control samples, and decreased to half or less by the treatment (Fig. 3). The force needed for the bending, decreases considerably. The longitudinal compression resulted in a decrease of *MoR* with 3.2% and *MoE* with 59.0%. While the deflection of control samples averaged 9.3 mm till the break, both compressed and short-time relaxed samples had at least 3 times higher deflection (Fig. 4a), and almost the same force needed for the bending process. Furthermore, with a large increase of relaxation time (*OLm* samples) the deflection increased so much that the samples did not break during the bending tests. The high deflections mean high bendability, which is the most important property for utilization of the material (Fig. 4b). For *OLm* samples the maximum deflection is at least 6 times higher than with control samples (Fig. 4b).

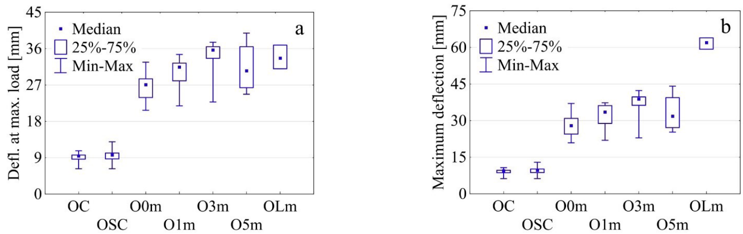

Fig. 4: The deflections at the highest bending forces (a), and the maximum deflections (b) during 4 point bending test. Abbreviations: OC-control sample; OSC-steamed control sample; O0m, O1m, O3m, O5m-longitudinally compressed samples with 0, 1, 3 and 5 minutes of relaxation time; OLm-compressed and long-time relaxed sample.

It can be also seen that the point of the maximum force and the point of break move away from each other with the increasing relaxation time. Comparing Fig. 4a and Fig. 4b, the deflection at highest load and the deflection at the breakpoint move away from each other with the increased relaxation time. This indicates an increasing ductility due to increased relaxation time. The deformability has a strong inverse correlation with *MoE* (Ashby and Jones 1996). Fig. 5 represents the change of the *MoE*. The slope at the beginning of each graph decreases with the increased relaxation time.

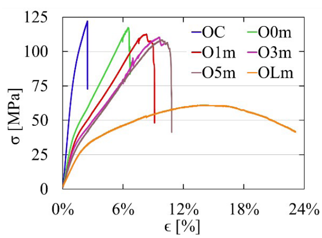

Fig. 5: Typical Relative deformation – Bending stress graphs for the different treatments. Abbreviations: OC-control sample; O0m, O1m, O3m, O5m-longitudinally compressed samples with 0, 1, 3 and 5 minutes of relaxation time; OLm-compressed and long-time relaxed sample.

The initially peaky graphs of the control samples observed at the greatest force (Fig. 5), gradually become rounded both by compression and increasing relaxation time. Finally, *OLm* samples can undergo significant plastic deformation before fracturing: they show ductile properties (Hayden et al. 1965), as also represented in Fig 6. All these changed properties led to a new material with the major advantage of easy bendability.

Mechanical correlations

A typical example for the decrease of the compression force during relaxation can be seen in the Fig. 1. Compression stress is calculated by dividing compression force with the cross-sectional sizes of the sample. The compression stress starts to decrease right after the end of compression (Fig. 3). In the first minute of relaxation the decrease of the compression stress is 32.6% and then the decrease slows down. However, it does not stop. The compression stress of *OLm* samples has already decreased 74.6% which indicates the change of internal stresses in wood. By longitudinal compression and short-time relaxation the decrease of *MoR* is not pronounced (Fig. 3), but with the long-time relaxation, it decreased by 56.9 MPa, to the half of the original value. Considering

MoR, the long-time relaxation is not necessary. At the same time, stress at 5 mm load span displacement and *MoE* decrease significantly even with the longitudinal compression (Fig. 3). The long-time relaxation resulted in a *MoE* of 1.9 GPa, which means an 81.0% decrease and stress at 5 mm load span displacement of 29.3 MPa which was a decrease of 70.7%. Some mechanical properties decrease while the remaining shortening increases during relaxation and thus the wood suffers structural changes, especially in the first minute. A T-test produced correlations between the compression stress change and all other physical and mechanical properties (Tab. 3). This is true also for the remaining length change after drying to 12% and the other properties, with 95% reliability.

Tab. 3: Regression summary for dependent properties. Abbreviations: MoR-modulus of rupture; MoE-modulus of elasticity.

Variable 1	Variable 2	R	$R^2_{adj.}$
Compression stress change (sample number: 45)	Remaining length change after drying to 12%	**0.9511**	0.9024
	Stress at 5 mm load span displacement	0.6564	0.4176
	MoR	0.5563	0.2934
	MoE	**0.7729**	0.5880
	Deflection at maximum load	0.2656	0.0490
	Maximum deflection	**0.8067**	0.6427
	Relative deformation	**0.8793**	0.7679
Remaining length change after drying to 12% (sample number: 65)	Stress at 5 mm load span displacement	0.6750	0.4469
	MoR	0.5528	0.2946
	MoE	**0.7433**	0.5453
	Deflection at maximum load	0.3535	0.1110
	Maximum deflection	**0.8210**	0.6689
	Relative deformation	**0.9048**	0.8159

In Tab. 3 the coefficient of correlation (R) and the adjusted coefficient of determination ($R^2_{adj.}$) are enumerated in the last two columns. The latter indicator does not take into consideration the points that do not fit the model, so it gives more accurate feedback than the coefficient of determination (R^2). Its difference from 1 shows the random mistakes in the experiment (material differences, measuring errors, sample differences, etc.). This means, despite the natural variability of wood material and its high modification ratio by the treatment, we got adequate indexes to predict some properties. The regression is weak between the remaining length change and the deflection at maximum load, *MoR* and stress at 5 mm load span displacement. The other four properties (marked in bold in Tab. 3) fit the trendlines much better. Based on the correlations, if we know the properties of a few samples, we can quite safely determine the bendability of the whole population, based on the compression stress change during the relaxation process. Furthermore, if we do not know the change of the compression stress during relaxation, the remaining shortening can also indicate the bendability of the sample. Both can be used to give predictions of the maximum bendability of all similarly prepared samples made from the same raw material, right after the production.

Rigidity

The stress-strain curve for a rigid material is typically linear over the full range of strain and the breaking point is sharp (Roylance 2008). But before fracture significant plastic deformation occurs on the curve of a ductile material. The graphs in Fig. 5 become more arched with the increased relaxation time, and they have less sharp breakpoints. This way we can see that the crack became less rigid as well. Fig. 5 clearly shows that the maximum bending stress appears at a deformation which is before the breakpoint, already with the O5m sample. This change of the graphs indicates the even higher plasticity properties of the material. The breakpoint disappears in the long relaxed samples, which means the original rigidity of oak wood is fully gone. The change of rigidity can also be seen on the images made after the bending examinations (Fig. 6). At the outside of the bend occurs tensile stress, the fracture shows tough material properties for control samples (Fig. 6 OSC) (Kollmann 1951, Molnár 1999). This fracture image is normal with oak wood. With longitudinal compression (Fig. 6 O0m) and short-time relaxation (Fig. 6 O5m) the fractures became tougher and the remaining tortuosity higher, and finally the samples relaxed for a long-time (Fig. 6 OLm) did not break in the course of the bending test.

Fig. 6: Images of crack patterns for different modification methods. Abbreviations: OSC-steamed control sample; O0m, O5m-longitudinally compressed samples with 0 and 5 minutes of relaxation time; OLm-compressed and a long-time relaxed sample.

When the strain exceeds the elasticity limit, some of the material deformation becomes irreversible, and therefore remaining strain is the result after the unloading (Roylance 2008). The strain - belongs to the elasticity limit - decreases with longitudinal compression and with increased relaxation time (Fig. 5). The remaining tortuosity will also be larger, as shown in Fig. 6. Furthermore the permanent deflection of *OLm* samples is the same as that of the O5m samples (Fig. 6). The maximum deflection of *OLm* samples was twice as great, so the spring-back of *OLm* samples was extremely large after bending.

Length change

The remaining shortening after pleating represents the resistance of wood against the compression, and the remaining shortening is proportional with the force needed to bend the wood (Segesdy 2003). The length change after drying to 0% moisture content was calculated from the difference of length changes under wet and normal conditions. After longitudinal compression, shrinkage is 3 times higher during the drying (Fig. 7). The relaxation process increases the shrinkage too, from 0.51% to 0.68% in the first minute. With the long-time relaxed samples, the shortening amounts to 0.94% during drying. Compared to control samples, this means about 6 times higher shrinkage. The explanation of this phenomenon can be due to the curved cell walls, because this way a part of the far greater transverse shrinkage is added to the longitudinal shrinkage.

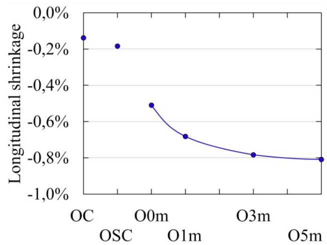

Fig. 7: Length change during the drying process, depending on the relaxation time. Abbreviations: OC-control sample; OSC-steamed control sample; O0m, O1m, O3m, O5m-longitudinally compressed samples with 0, 1, 3 and 5 minutes of relaxation time.

Optimal relaxation time

Due to the good correlation between the flexibility and compression stress (Tab. 3), the latter property also can be used to get the optimal relaxation time. The time-force graph (Fig. 1) is always continuous and has no breakpoint in the relaxation phase. Analyzing the change of compression stress over time, in the first 2 seconds, the compression stress falls by 12.1%. In the next 2 seconds, the compression stress falls by 4.7%, then only by 3.1% and by 2.4%, and so on, compared to the starting value. Compared with the initial decrease (12.1%), a value of 0.5% is considerably smaller, about only the twentieth of it. Hence, when the decrease never exceeds 0.5% per 2 seconds, the change of the compression stress can be considered as slow. This is an experiential value where the productivity and the required properties meet practically. The terms can be seen in Tab. 4.

Tab. 4: Optimal relaxation time, where the change of compression stress is below 0.25% per second. Abbreviations: O1m, O3m, O5m-longitudinally compressed samples with 1, 3 and 5 minutes of relaxation time; OLm-compressed and a long-time relaxed sample.

Treatment name	Optimal relaxation time (sec)			
	Average	Coefficient of variation	Minimum	Maximum
O1m	48.9	17.3%	33.5	59.1
O3m	51.6	20.4%	31.7	69.5
O5m	46.6	23.6%	38.9	63.0
OLm	47.1	28.4%	35.5	61.8
Total:	**49.8**	**19.9%**	**31.7**	**69.5**

If we are looking for the optimal relaxation time based on the mechanical changes, 1 minute relaxation is suggested and it also has a safety reserve (Tab. 4). After 1 minute relaxation time, the maximum deflection increases to 110% compared to the compressed wood without relaxation, and to 353% compared to the control samples, in accordance with the decrease of *MoE* (89.3% and 37.0%, respectively). Compression stress decrease to 67.4%, bending stress at 5 mm load span displacement to 43.9% and *MoR* to 95.4% by longitudinal compression and 1 minute relaxation time, compared to the control samples.

Of course, to meet individual demands, longer relaxation times can be chosen. A long-time relaxation is needed to reach the maximum deflection, but this is very slow both for industrial and laboratorial production. However, maximum deflection increases a lot (Fig. 4b), just as shrinkage increases during the drying process.

Resting

In this experiment, 2 wood species were dried in 2 ways, and all of them were also produced in a rested version. The treatment methods and the mechanical changes that occurred by resting are shown in Tab. 5.

Tab. 5: The property changes of pleated wood, due to resting. Abbreviations: MoR-modulus of rupture; MoE-modulus of elasticity.

	MoR	MoE	Deflection	Shrinkage change
Oak compressed, careful drying	0.8%	1.7%	0.0%	12.0%
Oak compressed, intensive drying	0.8%	2.7%	-4.4%	-1.1%
Beech compressed, careful drying	0.2%	-0.4%	2.4%	7.9%
Beech compressed, intensive drying	0.1%	0.4%	-3.9%	-9.0%

From the point of view of resting, the intensity of the drying process is not important as we are now investigating only the relative changes in the properties of rested and non-rested material. It was hard to ensure even a 0.1 mm accuracy in shrinkage change measurements, and after further calculations we always had less than 1 mm average differences between the different methods. This means, the 12% and lower shrinkages shown in Tab. 5 are very low alterations, which are between the margins of errors. The mechanical properties (*MoR* and *MoE*) change less than 5% such as the deflection, as well as the deflection during the bending tests. Using 95% level of significance, the Fischer-LSD analysis could not find any significant differences between the properties of rested and non-rested materials, so resting can be considered as an unnecessary process.

CONCLUSIONS

This study was performed to determine some mechanical properties such as *MoE* and some physical properties such as deflection of the longitudinally compressed Sessile Oak, taken with different relaxation times, as well as to determine the correlations between these properties. The effect of the resting also belongs to this topic.

The reason for the new properties of longitudinally compressed and relaxed wood can be explained by cell wall deformations (the cell walls seem like a plisse shade). Therefore a descriptive name for the treatment is “pleating”. Higher compression stress reduction during relaxation means greater shortening of the material remains, and these are indicators of higher deflection ability and higher relative deformation, lower *MoE* and lower *MoR*. This statement is valid for the average data to compare the different relaxation times. For individual samples, only MoE, maximum deflection and relative deformation can be predicted. Furthermore, pleating produces 3-6 times greater shrinkage in the longitudinal direction during the drying process, depending on relaxation time.

After 1 minute relaxation time, the change of the material properties slows down extremely, so the generally recommended relaxation time is 1 minute as an ideal combination of economic relaxation time and increasing of bendability. This results in an increase in maximum deflection during 4 point bending tests to 353%, and in a decrease to 37% in *MoE* and to 44% in bending stress at 5 mm load span displacement, compared to the control samples. To meet special requirements for the product, both the compression ratio and the relaxation time can be changed.

A long relaxation time results in a wood material with plastic properties with a 6 times higher deflection compared to the compressed samples without relaxation, still without breaking, but this slows down the production and increases its costs. Resting after pleating does not significantly affect the properties of the wood material and therefore resting is unnecessary. The wood is ready to bend immediately after pleating.

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