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Factors Influencing Behaviour of Solid Wood Bending Process

Čimbenici koji utječu na proces savijanja cjelovitog drva

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ABSTRACT • *The effect of temperature and moisture on the behaviour of solid wood is a well-known fact that directly affects wood creep as well. Wood creep includes three types of behaviour, such as viscoelastic creep, mechano-sorptive creep, and pseudo-creep and recovery. All these types can occur simultaneously, and it is sometimes complicated for researchers to isolate or distinct one from another. This paper presents a review of literature on wood rheology and creep properties, as well as factors that influence them, mainly time, temperature, and moisture content. The study of the viscoelasticity and wood creep is very important for gaining knowledge to be applied in solid wood bending.*

KEYWORDS: *solid wood; creep; rheology; viscoelastic; solid wood bending*

SAŽETAK • *Utjecaj temperature i vlage na ponašanje drva dobro je poznata činjenica koja ima izravan utjecaj i na puzanje drva. Puzanje drva obuhvaća tri tipa ponašanja: viskoelastično puzanje, mehaničko puzanje uzrokovano sorpcijom vode te prividno puzanje i oporavak. Svi ti tipovi ponašanja drva mogu se pojaviti istodobno, a istraživačima je katkad komplicirano izolirati ili razlikovati jedan tip od drugoga. Ovim je radom prikazan pregled literature vezane za reologiju i svojstva puzanja drva, kao i čimbenika koji na njih utječu, a uglavnom su to vrijeme, temperatura i sadržaj vode u drvu. Proučavanje viskoelastičnosti i puzanja drva iznimno je važno radi stjecanja specifičnih znanja potrebnih za istraživanja i razvoj tehnološkog procesa savijanja cjelovitog drva.*

KLJUČNE RIJEČI: *cjelovito drvo; puzanje; reologija; viskoelastičnost; savijanje cjelovitog drva*

1 INTRODUCTION
1. UVOD

Wood is a 3-component fibre-reinforced biocomposite. Its cells are multi-layered tubes with closed ends. Individual cells have four distinct cell wall layers. Those layers are primary, S1, S2, and S3 and each of them is composed of a combination of cellulose microfibrils, lignin and hemicelluloses. Microfibrils arrangement is the basic of dividing cell wall layers (Cave and Walker, 1994). Lignin is an amorphous phenol, and the cellulose and hemicellulose are linear polysaccharides (Tabet and Aziz, 2013). According to Arzola-Villegas *et al.* (2019), primary wall and middle lamella are grouped into a layer called the compound middle lamella due to them being almost identical. The middle lamella provides adhesion between the cells and interconnects them. It is mostly made of lignin

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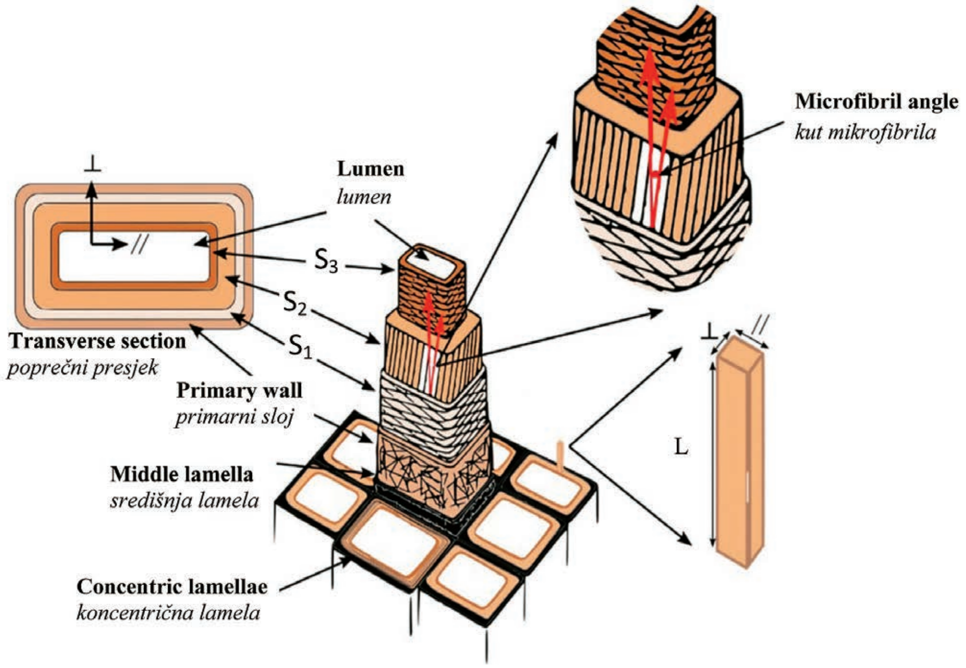

Figure 1 Schematic of wood cell wall layers, patterns represent cellulose microfibril orientations (Arzola-Villegas *et al.* 2019)
Slika 1. Shema slojeva stanične stijenke drva; uzorak predočuje orijentaciju celuloznih mikrofibrila (Arzola-Villegas *et al.*, 2019.)

with some hemicelluloses. Schematic of wood cell wall layers in Figure 1 shows the patterns that represent the orientation of cellulose microfibril.

Navi and Sandberg (2012) stated that the S2 layer is thicker than S1 and S3 and that therefore it contributes the most to the mechanical and physical properties of the cell wall. For these reasons, the term microfibril angle (MFA) is usually applied to the orientation of cellulose microfibrils in the S2 layer in literature. It refers to the angle between the direction of cellulose microfibrils and the longitudinal cell axis. According to Barnett and Bonham (2003), wood mechanical properties are profoundly affected by differences in microfibril angle since the S2 layer represents the cell wall major component. Tensile strength and stiffness quickly decrease as the MFA increases (Mary Treacy *et al.*, 2001). This means that wooden elements with long cells and low microfibril angles would make great material for bending due to better tensile strength, which can cause problems.

Bending of wood is the type of processing with certain levels of mechanical destruction. It is often used in manufacture of furniture, ships and boats, sports equipment, fishing rods, bows and other kind of tool equipment. Higher material utilization is the most important advantage of wood bending. Some of other advantages are small investments in technology, and higher strength and stiffness of bent wood elements than those of sawn elements. For example, chairs produced of bent elements have greater load-bearing capacity (e.g., legs, back rest, and arm rest) than those of sawn elements. Greater strength of bent elements is due to continuous grain slope. Sawn elements have their grain slope cut off in certain parts, which lowers their strength and load-bearing capacity.

When solid wood bends, it stretches on the convex (outer) side of bent piece and compresses on the concave (inside) side. Therefore, convex side is longer than the concave side. Bent elements tend to return to their original position due to high remaining stresses caused by deformation of wood. For these reasons wood is softened by moisture and heat or in some cases with chemicals because that way stress development is limited. It allows wood elements to retain their bent shape. Wood, even after softening or plasticizing, cannot be stretched very much but it can be significantly compressed, which is the reason why manufacturers are compressing wood while at the same time preventing stretching along the outer (convex) side (usually by using a metal strip). Some prior knowledge of wood creep and rheology of materials (mainly wood) is required to bend wood properly and precisely without a high rate of damage and discard.

Wood is a natural polymer, and it creeps under imposed stress, and it is a viscoelastic mechanical problem that is mostly encountered during processing and utilization. Wood creeps during the drying of solid wood, as well as during long-term loading of wood members such as roof frames, beams, columns, and walls. It is necessary to understand wood creep properties and the influence of creep on wood and wood products in long-term service conditions to make rational and efficient use of it (Jin *et al.,* 2016).

Pustaić and Cukor (2009) called material creep "a phenomenon where stresses and strains that occur under the load of a deformable body change over time even if the load is time-invariant (constant)". On the other hand, Curtu *et al.* (2015) defined the rheological behaviour as the system that strains under external load in a certain amount of time and under the influence of environmental factors. This phenomenon was also divided by Pustaić and Cukor (2009) in two forms; the first form is called creep – the change in deformation over time, while the second form is called relaxation – the change in stress. Fridley (1992a); Fridley (1992b) characterized wood as viscoelastic material governed by creep behaviour. Creep can be plastic and elastic, which means that, with plastic creep, the deformations are basically irreversible (only slight decrease in deflection) after unloading the element, while with elastic creep, deformations decrease over time after removing the load from the element and they completely disappear after some time. Hunt (1999) claims that for many structural applications the most important mechanical property of wood is its resistance to deflection, including elastic and creep deflection. Many factors affect rheological phenomenon. Curtu *et al.* (2015) listed some of them to be temperature and air humidity or moisture content (MC) of rheological system (in this case wood MC), various radiations in term of intensity, duration, and type – UV, IR, X, geometry of the elements; loadings in terms of intensity, variation, duration; defects; aggressive environment; composition, material properties; and combinations of these factors. Rheology science is based on the theories of the strength of materials, thermodynamics, chemistry and materials science, but in terms of application, it provides a personalized analysis or diagnosis according to the condition of the structures/systems used (Curtu *et al.,* 2015). Hunt (1999) suggests that creep includes three distinct types of behaviour, which are difficult to separate because they can all operate simultaneously. The three types mentioned by Hunt (1999) are time-dependent (viscoelastic) creep, mechano-sorptive (moisture-change) creep, and the pseudo-creep and recovery ascribed to differential swelling and shrinkage.

2 MECHANICS AND RHEOLOGY OF WOOD
2. MEHANIKA I REOLOGIJA DRVA

The study of strain behaviour of polymeric materials, which is time-dependent, is called creep and it is defined as continuous deformation in time when exposed to a continuous load (Peng *et al.,* 2017). In terms of creep behaviour, it is well known that, when stress is applied, an immediate elastic strain appears and in case of longer period exposure, long-term strain is developed. Navi and Stanzl-Tschegg (2009) and Morreale *et al.* (2015) described wood as a sustainable building material, which shows creep behaviour due to its viscoelastic nature. Creep of wood as viscoelastic material occurs as a combination of elastic deformation and viscous flow, known as viscoelastic deformation (Bodig and Jayne, 1993). As already mentioned in the introduction, a variety of factors influence wood creep behaviour, some of them being stress level, composite formulation, temperature, and MC (Liu, 1993; Chen and Lin, 1997; Hogan and Niklas, 2004; Zhang *et al.,* 2007). The factors listed above are a more simplified explanation of rheological factors than that of Curtu *et al.* (2015) presented in the previous chapter. Leicester (1971) reported that, while drying under a load, the deflection increase is more influenced by MC than by time. Hunt (1999) suggests that the main design parameter for timber is deflection which is the addition of two types of behaviour, namely elastic deflection and creep. The second component of deflection, creep, is of two types as already mentioned earlier in this paper: viscoelastic and mechano-sorptive. These two types have traditionally been considered independent and additive but contrary to previous views, the experimental results of Hunt (1999) led to the conclusion that time-dependent creep and mechano-sorptive creep are different means of reaching the same creep result. In addition to the time-dependent creep and mechano-sorptive creep, Hunt (1999) also mentions a pseudo-creep and recovery phenomenon, which is manifested during continued moisture cycling, in which the creep deflection eventually increases during desorption but decreases during sorption. He ascribed this to differences in the normal longitudinal swelling and shrinkage of wood as stated by Hunt and Shelton (1988) who claimed that "a tensile strain resulted in a smaller shrinkage coefficient, while a compression strain resulted in a larger one". This indicates that pseudo-creep and recovery are approximately a reversible phenomenon, contrary to the other two types of creep that are irreversible while the loading is maintained. Curtu *et al.* (2015) explained the creep phenomenon that appeared in the timber by the development of dislocation between the molecule chains and the destruction of the primary and secondary links, by occurrence of cracks and shears between the wood fibres. On the other hand, Kollmann (1968) stated that the elastic properties of wood are influenced considerably by knots, as they have cross grain or interlocked fibres. Furthermore, Hunt (1999) considers that deflection has acquired greater importance since the increased use of 'plantation grown' timber, which means that more commercial timber is fast grown *(i.e.,* wide growth rings) and is cropped at a sufficiently early age to contain a significant proportion of 'juvenile' wood. He also claims that juvenile wood can creep up to five times as much as mature wood and that all these factors mentioned result in a material that has lower elastic modulus and creeps significantly more than slow-grown mature wood. Kollmann (1968) mentions investigations carried out by Kellog (1960), which indicate that ultimate tensile strain of wood including accumulated creep increases after repeated stressing in tension parallel to the grain and that there is an indication that this increase in ultimate strain is a result of the increased strain due to the creep that occurred during the cycling period.

The general rheological model was developed under the assumption of strain which is divided into parts, meaning that the total mechano-sorptive creep strain is the sum of all the above strains: elastic strain, viscoelastic strain at constant MC, free shrinkage/swelling strain, mechano-sorptive strain, and thermal expansion/contraction strain (Vici *et al.,* 2006; Guo, 2009). However, Peng *et al.* (2017) claim that this rheological model and its application is still not understood well enough due to wood viscoelastic properties that depend on climate conditions, complex anatomic structure, stress level, and load model.

3 INFLUENCE OF MOISTURE AND TEMPERATURE ON WOOD CREEP

3. UTJECAJ VLAGE I TEMPERATURE NA PUZANJE DRVA

Wood adsorbs and desorbs moisture with changes in conditions such as relative humidity and temperature, which is the reason why it is considered a hygroscopic material. The changes in MC of wood lead to swelling and shrinkage, which are dimensional changes that happen when wood adsorbs or desorbs moisture. For that reason, it is expected that MC and especially its changes would have effect on wood creep. Hunt (1999) named a second type of creep, which is mentioned and associated with transient moisture-content changes, as mechano-sorptive creep, while Kaboorani *et al.* (2013) named dual effect of wood moisture and the load mechanical absorption effect. Armstrong and Kingston (1960) were the first ones that discovered the effect of moisture changes on creep and reported it. Hunt (1999) summarized this phenomenon in three statements: “the deflection of wood under load increases massively during moisture changes, whether sorption or desorption, and the final creep compliance is greater than it would be expected at either the lower or the higher MC”; “the final deflection depends mainly on the size of the moisture step and is little affected by its duration”; “and while the moisture is cycled within a given range there is a gradual decrease in creep rate; any increase to a yet higher MC causes the creep rate to increase to the original highest rate”. Jin *et al.* (2016) put it simply by saying that moisture in wood, acting as a plasticizer, strongly affects the wood viscoelastic properties. It is well known that as the wood dries below fibre-saturation point its strength increases and that above fibre-saturation point the effect of MC on static strength is negligible. Following these claims, Kollmann (1968) suggests that above the fibre saturation point free liquid water filling the coarser capillaries in vessels, tracheids and other elements of the wooden tissues does not affect strength and elastic properties. This would suggest that, when wood is exposed to moisture changes, deformation would be higher than when it is exposed to constant environmental conditions for the same time (Bazant and Meiri, 1985; Nakano, 1999). It can be concluded that MC would have an impact on creep properties of wood as well as its lowered mechanical properties. Jin *et al.* (2016) suggests that moisture in wood (when MC < 30 %) could affect the internal hydrogen bonds between wood polymers, which would directly influence wood plasticity and deformation. When wood is under load, adsorption and desorption cause additional deflection, hydrogen bonds break during desorption, which leads to an increased response in strain (Gibson, 1965).

Hoffmeyer and Davidson (1989) related the process of forming, breaking, and reforming of hydrogen bonds to slip planes in the cell walls. Slip planes form faster and at lower stresses when exposed to varying moisture conditions than at constant MC.

Hsieh and Chang (2018) separated their results into two distinct groups with MC higher or lower than the equilibrium moisture content (EMC) and found that the mechano-sorptive effect is time-independent. It is well known that temperature itself, as well as changes in temperature, have influence on strength, elasticity, and plasticity of wood. Kollmann (1968) claims that strength and stiffness of wood decrease with increasing temperature due to thermal expansion of the crystal lattice of the cellulose and due to the increased intensity of the thermal molecular oscillations. Researchers often have problems when conducting creep experiments with increasing temperature because retaining constant MC at higher temperatures is very difficult due to changes in MC that take place simultaneously with changes in the wood temperature; for these reasons, achieving desired MC levels at higher temperatures during creep tests was shown to be a technical difficulty (Jin *et al.,* 2016). Jin *et al.* (2016) conducted experiments on small birch wood samples conditioned at six MCs (0 %, 6 %, 12 %, 18 %, 24 % and 120 %) and temperatures ranging from 5 °C to 105 °C in increments of 10 °C. Their results of instantaneous compliance (IC), (which is reciprocal of modulus of elasticity), are shown in Figure 2. Based on data shown in Figure 2, it can be concluded that with increasing MC, the instantaneous compliance at the same

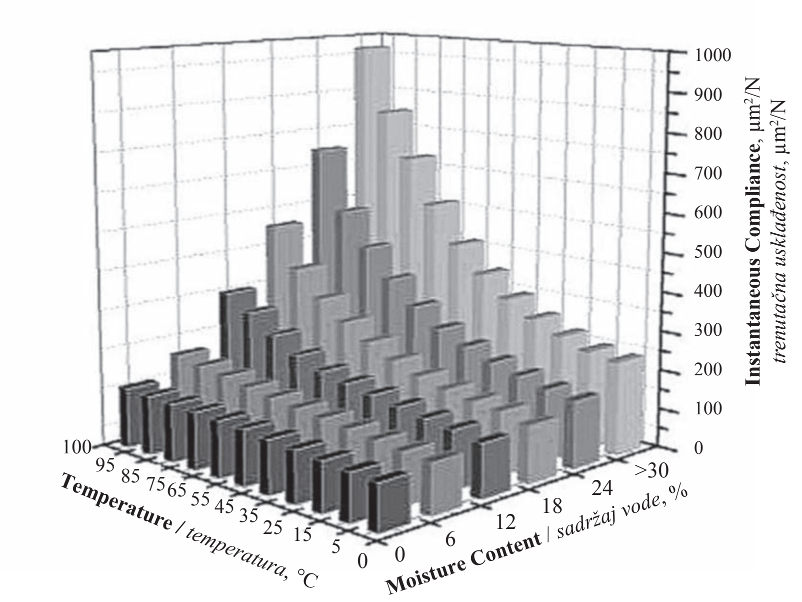

Figure 2 Instantaneous compliance of samples at 6 MCs and 11 temperatures (Jin *et al.,* 2016)
Slika 2. Trenutačna usklađenost uzoraka pri šest različitih sadržaja vode i 11 različitih temperatura (Jin *et al.,* 2016.)

temperature increased consistently, which agrees with previous research conducted by (Tissaoui, 1996; Moutee, 2006; Engelund *et al.,* 2012) and with Madsen (1992) who claimed that higher temperatures produce more creep, while at the same time samples were more affected by changes in MC than by temperature in a given range.

Yang *et al.* (2004) mention dependence of temperature on mechanical behaviour of wood (as a natural polymer) by saying that mobility of their molecular chain parts and chain segments are completely frozen when polymer components of wood are in the glassy state and that thermal motion only occurs at fixed positions. This again means that, when temperature is increased, molecular chains become loosened because of the repulsion between chains (Yang *et al.,* 2004; Engelund and Salmén, 2012). Dwianto *et al.* (1998b) divided these structural changes at molecular level in wood under steaming in three processes depending on treatment conditions. The first process they mention is hemicelluloses degradation, the second process is formation of cross-linkages between cell wall polymers and the last process is decomposition of hemicelluloses and lignin. They suggest that the difference in structural changes between the mentioned processes can be determined by creep measurement rather than by stress relaxation measurement. Results of Dwianto *et al.* (2000) research suggest that, with increasing pre-streaming time, degradation rate of cell wall polymers accelerated. They recorded large deformations at stress level of 0.71 of maximum compressive strength above 160 °C and concluded that creep deformation in those cases was sensitive to any degradation of cell wall polymers and that increasing temperature noticeably accelerated the increase of creep compliance while steaming above the mentioned temperature. Data from Armstrong and Kingston (1960); Gibson (1965); Hoffmeyer and Davidson (1989); Madsen (1992); Hsieh and Chang (2018); Peng *et al.* (2017) agree with the statement that changes in MC contribute more to creep than the initial MC. Hsieh and Chang (2018) reported that higher strain at same time point was noticed at wood samples with higher MC, as well as higher creep strain increment caused by higher MCs and higher desorption rates.

Wood creep knowledge in relation to moisture and temperature is also important while drying wood. For example, Zhan and Avramidis (2011) obtained valuable data in their research for kiln operators to choose the correct control strategy and theoretically valuable to determine the mechano-sorptive creep development mechanism during timber drying processes, which can help in obtaining a better description of the wood drying stress and drying strain.

4 TIME AS A FACTOR INFLUENCING WOOD CREEP

4. VRIJEME KAO JEDAN OD ČIMBENIKA KOJI UTJEČU NA PUZANJE DRVA

Creep phenomenon also depends on time, and it appears in many other materials, not only wood, and it is called time-dependent creep (Hunt, 1999). Hunt also claims that wood, as any other material, when considering its behaviour in terms of time requires temperature and MC as well as other relevant variables to remain constant. Sun and Frazier (2007) suggest that, in order to ease moisture control problem, absolutely dry wood rheology offers experimental advantage. Franck (2021) suggests that more detailed picture of time-related influence is needed to understand this behaviour fully for this information is not accessible experimentally. Furthermore, Franck (2021) claims that measurements consisting of a wide range of temperature are easy to make but when speaking in term of time changes that occur in less than a second or when time span is a few weeks long, such measurements become complicated.

Burgers (1948), Burgers and Blair (1949) and Curtu *et al.* (2015) mentioned Burgers model presented by Eq. (1), which characterises rheological deformation of wood based on its behaviour in terms of time:

$$\varepsilon = \varepsilon_e + \varepsilon_{ei} + \varepsilon_c = \frac{\sigma}{E_1} + \frac{\sigma}{E_2}\left(1 - \varepsilon^{\frac{E_t}{\lambda_2}}\right) + \frac{\sigma * t}{\lambda_1} \qquad (1)$$

Where, ε - strain (%)
ε_ε - elastic strain (%)
ε_{ei} - delayed elastic strain (%)
ε_c - flow strain (%)
σ - stress (MPa)
E - Young's Modulus of material (MPa)
t - time (s)/(h)/(days)
λ - viscosity (Pa*s)

Yuan-rong *et al.* (2008) described Burgers body as a simple model that describes creep behaviour of wood and noted that elasticity, viscoelasticity and creep, as parts of wood creep, can be determined from this equation. However, he stated that it can only be applied to the initial and second stage of creep, and that it cannot be applied to the end and breakage stage. Schniewind and Barrett (1972) suggest that wood can be considered as a linearly elastic material under some conditions, and as a linear viscoelastic material under other conditions for the purpose of stress analysis. When wood is exposed to sufficiently high temperatures, MCs, and stresses, it starts to show nonlinear behaviour (Bach, 1965). Data provided by Echenique-Manrique (1969) on stress relaxation shows that there are signs of non-linearity even at low levels of initial strain, but that the degree itself is very small over a large range of initial strain values, which means that there is no reason to discard the concept of wood as a linear viscoelastic material. Following these claims, Franck (2021) suggests that the solution arose from the experimental findings, which shows that time and temperature of time-dependent processes have similar effects on the rheological properties of linear viscoelastic materials. Franck (2021) describes master curves as a helpful way for understanding rheological behaviour of a polymer: viscoelastic properties depend on two main variables (time and temperature), which are separated by the super-position process that expresses the properties in terms of a single function for each. The time dependence of the material at a constant reference temperature is shown by the master curves, while the variation of the shift factor with temperature shows temperature dependence of the viscoelastic properties. Sun and Frazier (2007) conducted research on small southern yellow pine (*Pinus* spp.) and yellow poplar (*Liriodendron tulipifera*) dry wood samples. They applied

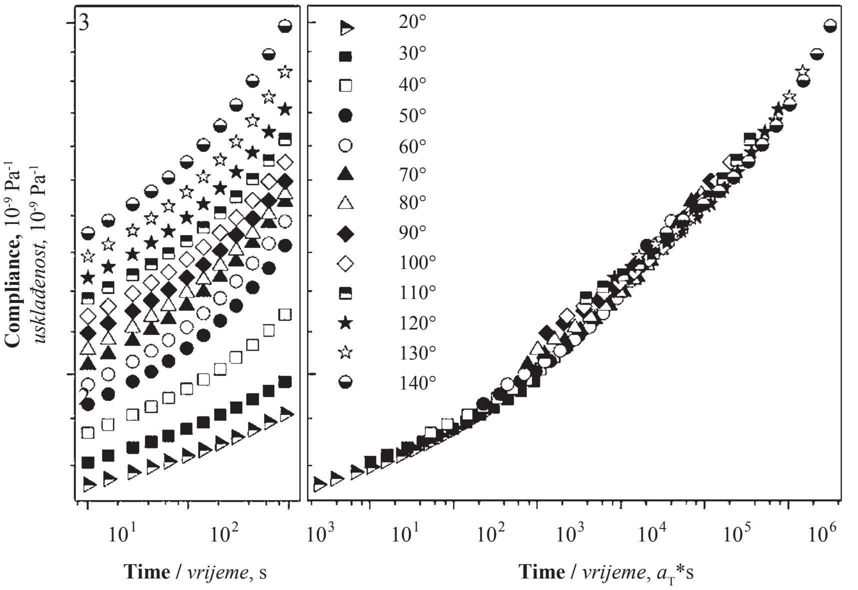

Figure 3 Raw creep compliance of southern pine from 20 °C to 140 °C (left). Master curve that results from simply shifting raw data in logarithmic time scale with a multiplicative shift factor (a_T) (no vertical shifting employed) (right). (Sun and Frazier, 2007)
Slika 3. Neobrađeni podatci o puzanju uzoraka crvenog bora pri temperaturama od 20 do 140 °C (lijevo). Glavna krivulja koja je rezultat jednostavnog pomicanja neobrađenih podataka u logaritamskoj vremenskoj skali s multiplikativnim faktorom pomaka (a_T) (bez vertikalnog pomaka) (desno) (Sun and Frazier, 2007.)

creep bending stress in tangential direction over a 10 °C to 170 °C temperature range for 30 min. Their results of raw creep compliance are shown in Figure 3, where it can be seen that the master curve is not smooth, meaning that the temperature dependence of the creep relaxation is not uniform across a given temperature range.

They concluded that the principle of time/temperature equivalence was valid for the dry wood creep response over a given temperature range, but it was true only for specimens that received a prior thermal treatment from 100 °C to 170 °C (for 30 min), at which specimens lost all moisture. The creep compliance is an established metric of the rate at which strain increases for a constant applied stress of viscoelastic materials (Tweedie and Van Vliet, 2006).

Ferry (1980) suggests that smooth master curve appears when time and temperature effects are identical. When smooth master curve occurs in a material, it is considered thermorheologically simple, but in this case specimens are thermorheologically complex due to failure of achieving smooth master curve (Sun and Frazier, 2007). According to Franck (2021), the master curve shows the time dependence (in terms of frequency) of the material at a constant reference temperature; the temperature dependence of the viscoelastic properties is shown by the variation of the shift factor with temperature.

5 APPLICATION OF RHEOLOGY IN SOLID WOOD BENDING PROCESS

5. PRIMJENA REOLOGIJE U PROCESU SAVIJANJA CJELOVITOG DRVA

As already mentioned in the introduction, when solid wood is bent, it stretches on convex side and compresses on concave side. This results in convex side being longer than concave side and that difference in length causes stresses to accumulate. These stresses then tend to bring back solid pieces to their original form; this phenomenon is commonly called spring-back effect. The reason why wood is being softened is to restrict development of the mentioned stresses. During the bending process, it is desirable for wood to creep/bend more due to the nature of the final product. Both high temperature and MC influence creep properties as already described in previous chapters. That is the reason why wood is exposed to high temperatures and MC due to temporary reduction in MOE of wood (which is preferred for its easier bending).

Navi and Sandberg (2012) explained the purpose of plasticization treatments. To make the curve, wood needs to be sufficiently softened so it can withstand the necessary compressive deformation without fracture. Furthermore, a combination of heat and moisture is an effective way of softening wood as wet wood is more plastic than dry wood and hot wood more plastic than cold wood.

Sandberg *et al*. (2013) stated that the main reason for the difficulty in bending solid wood is the low strain to failure in tension (about 1-2 %). However, after wood is plasticized, it becomes more plastic or semi-plastic, and this means that it can be softened and formed to keep its shape after cooling. Wood compressibility is greatly increased in the longitudinal direction after plasticizing, as much as 30-40 %, although its ability to lengthen under tension is not significantly affected.

Zemiar *et al.* (1997) stated that plastic deformability of wood increases with the decrease in MOE. Thermal plasticizing is a process of exposing wood to temperature and moisture in order to increase the plasticity of wood, and its main target is a temporary change in the mechanical and physical properties of wood. According to Báder and Németh (2019), the best pliability during bending is achieved when the moisture content of pleated wood is close to its fibre saturation point. According to Taylor (2008), the best MC for bending is around 25 to 30 %, and around 2 minutes of steaming per millimetre of width. Plasticisation of wood can also be done with chemicals such as urea and liquid ammonia, but it will not be described because it is beyond the scope of this paper. Gáborík and Zemiar (1997) suggest that it is most desirable to optimize the degree of plasticity with the degradation of components of the lignin-cellulose matrix. Gašparík and Barcík (2014) suggest that softening lignin, which is the main component of the middle lamella, is an important part of plasticizing wood because lignin properties reflect wood plastic properties. While steaming is the most commonly used method of softening wood, many manufacturing companies use the combination of steaming and high frequency (HF) process to unite the heating, plasticizing and drying in a single sequence. Bent samples are partially dried in (HF) press after bending. After unloading, the press samples are further fixated with wooden or metal tools to keep them firm to prevent the spring-back effect during drying of samples.

As already mentioned in the introduction, extensive knowledge of wood rheology and wood viscoelastic properties and a lot of trial and error tests is required to bend wood properly. Beech is the most common species of wood used for bending because of its good bending properties and its common use in manufacture of furniture. Likewise, oak wood is also a desirable species for bending because it is also often used in manufacture of furniture but is more complicated to bend than beech. Considering that, as expected, most of the literature describes and gives data on beech wood (*Fagus sylvatica*) bending. While in essence the process of plasticizing oak wood by heat and moisture is the same as that of beech wood, parameters such as initial MC before

Figure 4 Transverse cracks on convex side (tension) (photo: Mikšik, 2021)
Slika 4. Poprečne pukotine na konveksnoj strani uzorka (tenzija) (fotografija: Mikšik, 2021.)

Figure 5 Structure collapse on concave side (compression) (photo: Mikšik, 2021)
Slika 5. Urušavanje strukture na konkavnoj strani uzorka (kompresija) (fotografija: Mikšik, 2021.)

steaming, temperature of steaming, duration of steaming and press parameters vary. Many factors affect wood bending; some of them are radius of bending, species, MC, thickness, and width of wood, steaming time, fibre direction and defects (Niemiec and Brown, 1995). Niemiec and Brown also claim that wood selected for bending must be defect-free and have straight fibres, but in practice it is not always the case since wood pieces with knots and curled fibres can also be bent properly. Wangaard (1952) conducted an experiment on loss of modulus of rupture for beech and oak wood bent at a radius of 20 cm and concluded that the loss was 32.1 % for beech and 26.1 % for oak. Furthermore, he also stated that, with the increase of bending radius, the strength loss of beech wood decreased. Büyüksarı and As (2012) concluded in their research that the density of bent samples of oak wood and beech wood increased with the decreasing bending radius, which is logical due to the compression on the concave side of samples. They also stated that the increase of density was greater in oak wood than beech wood for all bending radii.

According to Peck (1957), compressive failures can occur if the plasticized wood is compressed excessively, if stresses are concentrated because of some defects and if the lines of weakness encourage shear failure. According to Báder *et al.* (2019), compression in longitudinal direction induces changes in wood tissue, which results in better bendability.

On the other hand, Stevens and Turner (1970) suggest that controlling the length and longitudinal tensile strain in the vicinity of the convex surface of a wood specimen during a bending process is important, because too small end-force causes longitudinal tensile failure, while an excessively large end-force causes premature longitudinal compressive failure. The smallest radius of curvature for any piece of wood is reached when both the inner and outer surfaces are on the point of fracturing. Adjusting end-stops can be used to regulate the amount of end-force and thereby impose the maximum compression on the concave surface of a bend, without, at the same time, inducing stress on the fibres near the convex surface (to strain them beyond the limit). Some of the wood defects encountered in literature so far are transverse cracks on convex side, structure collapse on concave side, defects around knots, cross section cracks, surface splitting of layers, cracks due to current breakdown in HF press, longitudinal crack on both sides and discoloration caused by metal strap in contact with woods that contain tannin.

6 CONCLUSIONS
6. ZAKLJUČAK

It can be concluded that both temperature and MC affect wood creep. It is more affected by changes in MC than by constant MC. Time-dependent creep also affects wood but to measure it requires temperature, moisture content and other important variables to remain constant. It is hard to conduct creep experiments with increasing temperature because retaining constant MC at higher temperatures is very difficult due to changes in MC, which take place simultaneously with changes in the temperature. The sum of the elastic strain, viscoelastic strain at constant moisture content, free shrinkage/swelling strain, mechano-sorptive strain, and thermal expansion/contraction strain makes mechano-sorptive creep stain. In order to bend wood more easily, it needs to be plasticized (treated with high temperature and moisture) properly to avoid unwanted defects. Bending methods and parameters for beech have already been determined in detail, which cannot be said for oak. For these reasons, our further studies will focus on finding optimal drying mode and optimal bending parameters (MC, thickness, width of wood, steaming time) for oak. Furthermore, experiments related to minimum radius for bending oak will be conducted. These parameters, if established properly, will have great industrial relevance for manufacturers that plan on producing furniture of bent solid oak wood in the future.

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