Wood Sci Technol (2014) 48:553–568
DOI 10.1007/s00226-013-0611-2

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Wood as a natural smart material

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Received: 8 April 2010 / Published online: 21 December 2013

Abstract The dominant feature of artificial smart materials is the “shape memory” effect. This phenomenon is based on frozen strains (FS). They were detected in wood fastened specimens during drying in the early 1960s. The integral law of wood deforming under loading and moisture content and/or temperature changes was subsequently formulated. This law takes into account the forming of FS. It was applied for the calculation of wood drying stresses. Stress memory and strain memory effects for wood were discovered. Wood has the ability to recollect the type of loading (tension or compression) which it had undergone. The difference between the free and restrained shrinkage is named “frozen shrinkage” (FSh). In calculations of drying stresses, it is more justified to use the FSh concept than “mechano-sorptive creep” (MSC). The MSC phenomenon is observed at *cyclical* change of moisture content in loaded wood. “Hygrofatigue” that reduces wood stiffness plays the main role in this process.

Introduction

At the plenary meeting in Cesis (2004), the distinguished scientist Anders Bjorkman presented a survey of the wood science development in the twentieth century. Emphasizing the complexity of wood structure, he said: “It will not be too pessimistic to state that we shall not learn to know the wood ultrastructure truths before 2050 or perhaps 3000. Anyhow, it is the most fascinating science to deal

Academy lecture presented at the 2009 IAWS Conference “Forests as a renewable source of vital values for changing world” on June 15–21, 2009, Saint-Petersburg, Moscow, Russia.

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with.” Profound knowledge of wood can be achieved by joint effort of biologists, chemists and physicists.

Nature that created wood has prompted mankind to produce diverse modern, artificial materials ranging from reinforced concrete to nanocomposites. Further studies on wood nanostructure discovered new possibilities of biomimetic approach to create effective materials. Material scientists predict a prominent role of artificial smart materials in the future. Recently, the term “intelligent” or “smart” material is being widely used. This term designates material that usefully reacts to exterior actions induced by changes in environmental parameters.

One of the main features of smart materials is the “shape memory effect.” It means that these materials after being forced to change their form are able to restore their initial form when the original physical conditions are recovered.

A very broad spectrum of smart materials was found that covers an area from deployable space structures to self-repairing auto bodies, switches, sensors, kitchen utensils and tools to minimally invasive surgery and implants in biomedicine.

In the current decade, for example, such problems in the behavior of shape memory polymers are becoming topical: fiber-reinforced elastic memory composites (Abrahamson et al. 2002), problems in the behavior of the shape memory polymers (Lendlein and Kelch 2002), internal stress induced by constrained expansion of memory polymer nanocomposites (Gall and Dunn 2004) and model development for shape memory polymers (Siskind 2008).

Features of wood as a smart material

Wood under external influences also reveals a number of useful, functional properties. Here are some examples.

Hygroscopicity of wood enables it to be used as a sensor of surrounding air humidity. Wood constructions of buildings regulate, to some degree, the air humidity in living premises by drying or humidifying the air at changing air humidity. Swelling of wood tightens joints in composites and structures. Pit props of pine and spruce wood emit crackling which is a warning of mine destruction. Acoustic emission is used for monitoring lumber stress state during drying. The sonorous ability of wood reveals itself in musical instruments. Piezoelectric properties of wood permit creating non-destructive methods of strength testing. This list of examples of wood being “intelligent” may be continued (Ugolev 2006).

Wood also possesses the dominant feature of smart materials—the “memory effect.” Wood scientists have started to study the shape memory effect a long time ago and probably earlier than polymer scientists did. As far back as then contemporary terminology for the description of deformative conversions was used.

The notion “memory of wood” was introduced at the beginning of the 1980s. Previously, some researchers (Takemura 1973, etc.) have used the analogous term for the indication of a purely temporal, rheological phenomenon. In the current case, this metaphor reflects the ability of wood to react to restore the initial physical state determined by its moisture content and temperature. “Wood memory effect” is based on “frozen strains” (FS).

Forming of wood frozen strains

Very big quasi-residual strains were experimentally discovered in the research of wood restrained shrinkage (Ugolev 1961). Later, they were named “frozen” strains. This was the reason for the development of the integral law of wood straining under loading and moisture content and/or temperature changes in 1971 in collaboration with Lapshin (Ugolev and Lapshin 1971; Ugolev 1976). The different character of wood deformation when drying and wetting was taken into account.

Equation (1) describes wood straining in the event of wood moisture content change. At independence of shrinkage (swelling) coefficients from stress level using temperature–moisture analogy, a similar equation can be applied for heating–cooling.

$$\varepsilon = -\beta W + \alpha W + H_1 \int_0^\tau \frac{\dot{\sigma}}{E(W,T)} \mathrm{d}\tau + H_2 \frac{\sigma}{E(W,T)} \tag{1}$$

where ε, strain; β, coefficient of shrinkage; $W = \Delta w$, moisture content decreases from limit saturation of cell wall (FSP); α, coefficient of swelling; σ, stress; E, stiffness modulus; T, temperature decreases from 100 °C; T, temperature decreases from 100 °C; $W(\tau)$, $T(\tau)$ and $\dot{\sigma}(\tau)$ are functions of time τ; H_1 and H_2 are Havisade’s functions for drying and wetting, respectively.

Let us consider more particularly the model of hygromechanical strains following this law.

The well-known components of wood deformation at stable moisture content are shown in Fig. 1. Loading of wood induces recoverable (elastic ε_e and viscous ε_v) strains and irreversible creep ε_c. When unloading, residual, plastic strains ($\varepsilon_r = \varepsilon_c$) remain.

The model postulates the quasi-static state when all time-dependant processes are completed.

The scheme in Fig. 2 shows the wood behavior at transition from wet to dry state and vice versa. Here, σ, stress; ε, strain; Δw, drop of moisture content. Short-time loading of wet wood leads to formation of elastic–viscous strain ε_{ev1} (0–1). Long-term loading adds creep ε_{c1} (1–2). Continuous, slow loading (0–2) and unloading (2–3) maintain residual strain ε_r (0–3). It is possible to consider various histories of wood behavior.

For example, wetting (4–0) and loading (0–2) lead to total deformation (0–2′). During drying under load (2–10), this strain is constant although wood stiffness increases. While unloading dry wood, elastic–viscous strain ε_{ev2} recovers (10′–11). Set ε_s (4–11) includes frozen strain ε_f (4–9) and residual strain ε_r, which is equal to creep of wet wood ε_{c1}.

Correctness of the model has been confirmed by numerous experiments. The important consequence following from this model—a constancy of strains at drying of bent spruce specimens and cooling of stretched specimens—was discovered at the beginning of the 70s (see Ugolev et al. 1980). Recently, this phenomenon has

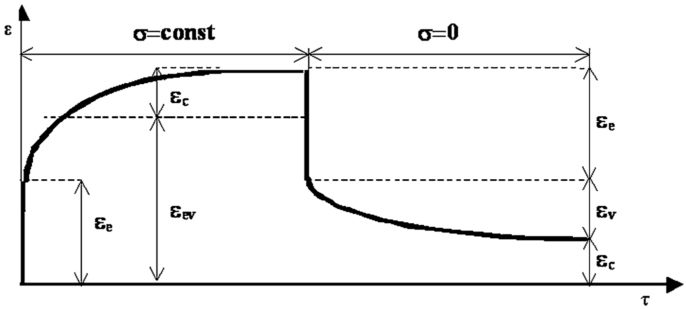


Fig. 1 Strain (ε)–time (τ) relationship of wood at constant moisture content

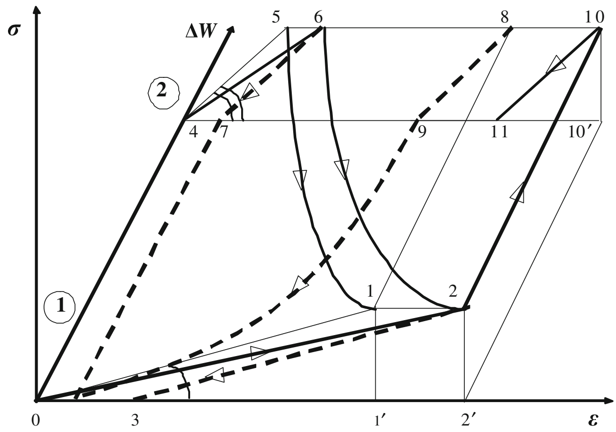


Fig. 2 Changes of wood hygromechanical strains

been revealed once more during cooling of bent spruce, beech and hornbeam specimens (Passard and Perré 2001).

As follows from the scheme (Fig. 2), frozen strain ε_f (4–9) is equal to the difference between elastic–viscous strains at the beginning and final moisture content (abscissas of points 1 and 5).

$$\varepsilon_f = \varepsilon_{ev1} - \varepsilon_{ev2} \tag{2}$$

Frozen strains are the result of temporary reconstruction of wood nanostructure under controlled load influence at increasing wood stiffness in processes of drying or cooling. The frozen strain disappears with wetting or heating.

Contribution of frozen strains to stress–strain state of wood at drying

Figure 3 shows the stress–strain relationship for wood loading during drying and unloading. Here: *w*, moisture content; ε_0, total strain; *E* and *E**, wood stiffness

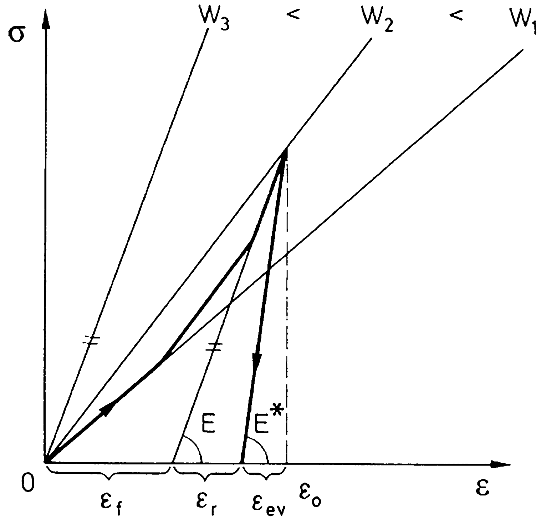


Fig. 3 Stress–strain relationship of wood during drying

modulus during loading and unloading, $E^* > E$. Frozen strains decrease tension stresses during drying, but they are the main reason for internal stresses (casehardening) of dried lumber as part of the set-strain:

$$\varepsilon_s = \varepsilon_f + \varepsilon_r \tag{3}$$

The frozen strain disappears with wetting or heating.

Frozen strains were taken into account in the elaboration of a calculation method for drying stresses. At the end of the 70s, the step-by-step method was suggested for a multi-sliced model of drying lumber (Ugolev et al. 1980). The following equation was proposed:

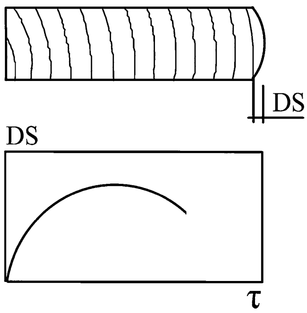
$$\sigma_i^j = \sigma_i^{j-1} + \beta \bar{E}_i^j \left[\Delta w_i^j - \sum_{i=1}^{n} \bar{E}_i^j \Delta w_i^j / \left(\sum_{i=1}^{n} \bar{E}_i^j \right) \right] \tag{4}$$

Here, σ, stress; β, coefficient of shrinkage; E, stiffness modulus; $\bar{E} = 0.5\,(E^j + E^{j-1})$, average stiffness modulus; Δw, moisture contents drop from limit of cell wall saturation (FSP); j, step number; i, slice number; n, number of slices.

Later, Skuratov supplemented this method with the slice by slice moisture content calculation method. A complex method for wood drying and wetting was also elaborated (Ugolev and Skuratov 1992). This method was used by many researchers in order to establish wood drying schedules.

Stress is one of the main parameters of lumber quality. At the beginning of last century, Tiemann proposed the "fork" method for qualitative evaluation of drying stresses. For wood stress measuring, it is necessary to determine elastic strain and modulus of elasticity. Initially, such method was developed for residual stresses (Ugolev 1952). This method was standardized in Russia and accepted in some other countries and gave the opportunity to raise the research of drying stresses to a

Fig. 4 Method of monitoring drying stresses by differential shrinkage



quantitative level. The use of the slicing technique for measuring strains only (McMillan 1955) allows obtaining rather approximate stress estimations. The development of wood drying stress measuring and monitoring methods has been considered in several monographs and papers (Ugolev 1959, 1971, 1992, 1997, 2005; Ugolev et al. 1980).

The non-destructive differential shrinkage (DS) method was proposed in 1967 for monitoring stresses during lumber drying. The controlled DS parameter is the difference of surface and central zone shrinkage of the board (Fig. 4).

In 1975, Lapshin and Pintus used FEM simulation of plain stress–strain state of wood for the first time to simulate DS drying schedules (Ugolev et al. 1980). The DS method was exercised in some other countries (Trebula 1981; Hill and Lessard 1986; etc.).

Memory effects of wood

There are two kinds of wood memory effect: "stress memory" and "strain memory". "Stress memory" reveals itself during wetting or heating of previously dried or cooled wood under load. This effect was discovered in collaboration with E. B. Schedrina at the end of the 70s (Ugolev et al. 1980). It is convenient to consider this phenomenon when temperature t changes. In Fig. 5, the "stress–strain" relationships are linearized as for an elastic body and $\theta = 100° - t$—drop of temperature.

Case a. The wood is loaded (1–2) at temperature t_1 and strain ε_0 appears. During cooling under dead load (2–3), the total strain ε_0 is constant. Further, during heating, the strain ε_0 remains constant, and stresses (broken line 3–2–6) can be determined as follows:

$$\sigma_R = E_t(\varepsilon_0 - \varepsilon_f) \tag{5}$$

where E_t is the modulus of elasticity at a given temperature t; ε_f is frozen strain

Wood "remembers" temperature (t_1) when loaded.

Case b. Analogous stress memory effect is observed at preserving constant size of unloaded wood with frozen strains (4–5) during heating. The stresses σ_r appearing during heating and $\varepsilon' = \text{const}$ are:

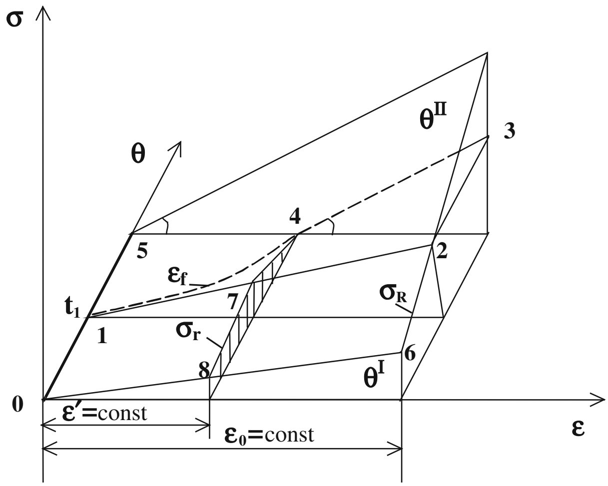


Fig. 5 Scheme of wood deformative conversions during heating

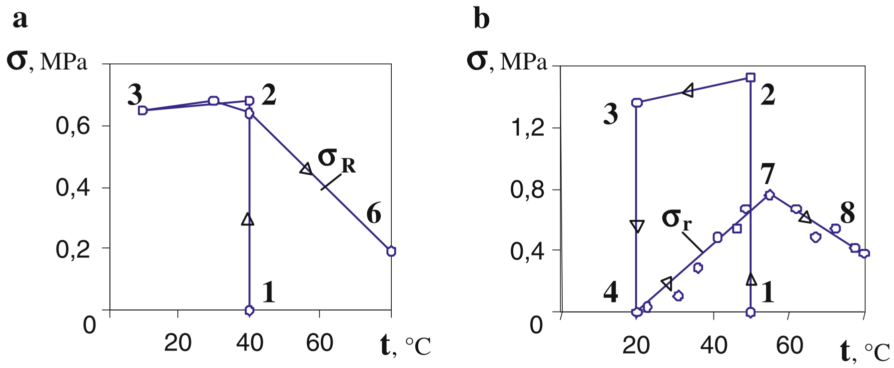


Fig. 6 Stress memory effect during heating: **a** loaded wood at constant total strain. *Pinus sibirica*, compres., tang. direct. across the grain, $\varepsilon_0 = 0.009$. **b** Unloaded wood at constant frozen strain. *Quercus robur*, tension, rad. direct. across the grain, $\varepsilon' = 0.007$

$$\sigma_r = E_t(\varepsilon' - \varepsilon_f) \tag{6}$$

Change of stresses σ_r shows a broken line (4–7–8).

Results of the experiments (Fig. 6) prove the predicted stress wood behavior for cases a and b.

The suggested model allows for predicting wood behavior and “strain memory effect.” Figure 7 demonstrates the results of one of the experiments on ash veneer. A flat-heated specimen was first bent (i.e., loaded), then cooled keeping this load, and then it was unloaded and heated again.

During cooling, the form of the bent specimen does not change (states b and c in Fig. 7). Heating removes “frozen strains” (Fig. 7d), and the specimen recovers its original form.

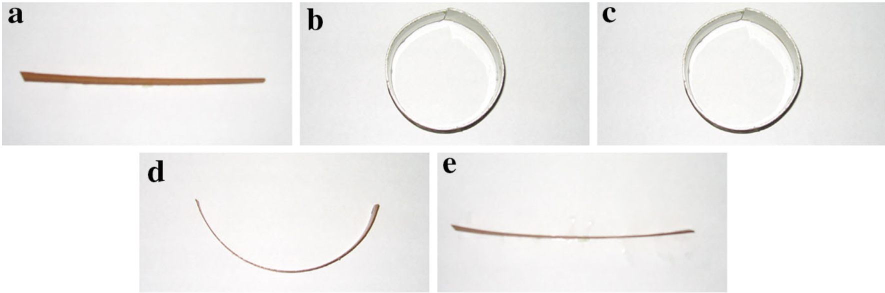


Fig. 7 Change of the form of ash veneer and "strain memory effect". **a** Original state (heated wood), **b** under load, **c** after cooling, **d** after unloading ("frozen strains"), **e** after heating

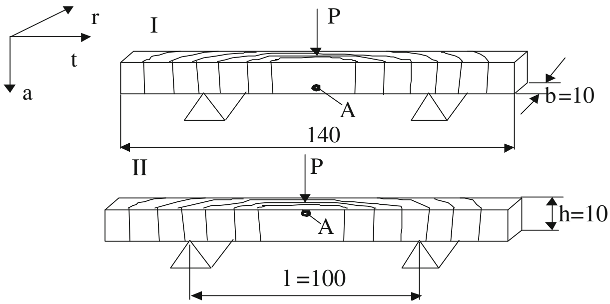


Fig. 8 Scheme of wood specimen loading

The "strain memory effect" depends on the deformation prehistory including various kinds of loading. For example, wood may be compressed and tensioned consecutively. Wood will memorize the kind of load which it had undergone.

The experiments on bending specimens were carried out in order to confirm these predictions (Gorbacheva 2000). By turning the bending specimen, the same point A was first put in the tension zone and then in the compression zone (Fig. 8).

Figure 9a shows the results of experiments on birch wood. Here, (1–2)—tension, (2–2)—cooling, (2–3)—unloading, then (3–4)—compression, (4–4)—cooling, (4–5)—unloading of wood. During heating, the size of the unloaded wood specimen first increases and then decreases (5–6–7). Such wood behavior depends on different kinds of thermofrozen strains in corresponding temperature ranges.

The drafts in Fig. 9b show the change of specimen deflections during the experiment more visually. After heating, an unusual (but predicted!) increase in specimen deflection was observed prior to the usual decrease in deflection.

Using frozen strains for improving veneer and lumber after drying

Similar phenomena appear at hygromechanical wood deformative conversions too. A synergetic effect was discovered when frozen strains had been formed during

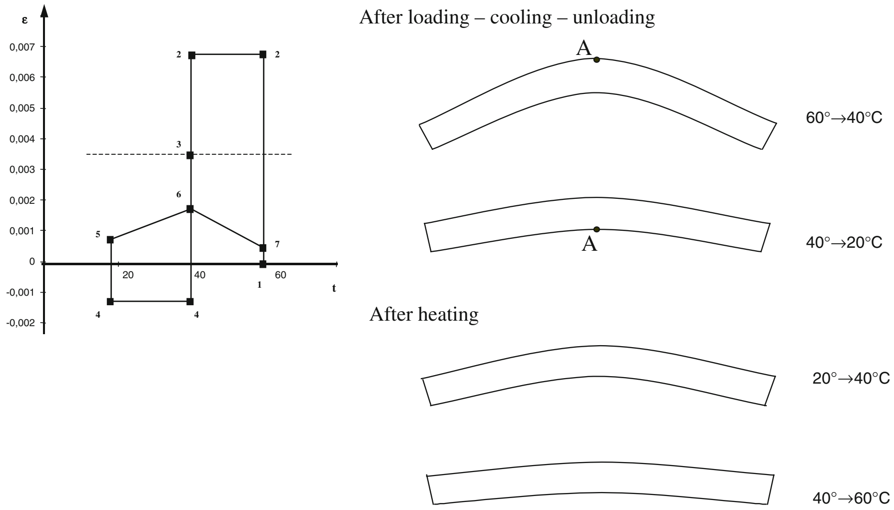


Fig. 9 "Strain memory effect" during heating of previously loaded (tension–compression) and then unloaded wood

simultaneous wood drying and cooling. In order to recognize the kind of constituent strain (thermofrozen or hygrofrozen) in complex strains, they were "marked" by the type of loading that had induced the strain. This approach was applied for developing the method of removing veneer waviness by creating counter frozen strains of both types (Ugolev et al. 2004).

The model of the authors allows for calculating not only current drying stresses but also determine set-strain ε_s. The main part of ε_s is frozen strain ε_f. Conditioning moisture–heat treatment is used for removing set-strain.

Early deformative conversions during drying and conditioning of lumber in a two-stage treatment were considered (Ugolev 1986). Figure 10 demonstrates the stress–strain behavior of the surface zone of a board during drying and conditioning. Here: tension loading at drying (0–1), unloading due to the internal zone shrinkage (1–2), set-strain (0–2), compression due to proceeding drying of the internal zone (2–3), small stress increase takes place at wetting (3–4) and sharp stress decrease at sub-drying with cooling (4–0).

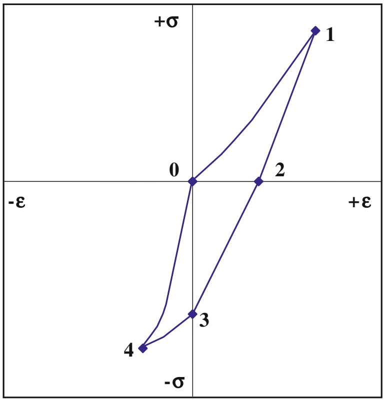
Later, greater efficiency for set-strain removing of sub-drying with simultaneous cooling was proven experimentally (Ugolev and Skuratov 1988).

Wood deformative conversions at loading and moisture content change

Change of wood nanostructure at hygromechanical strains

The research by Ugolev et al. (2007) conducted in collaboration with the Institute of Solid State Physics using IR spectrum method showed that during drying of the

Fig. 10 Wood stress–strain behavior of the surface zone of a board during drying and conditioning moisture–heat treatment



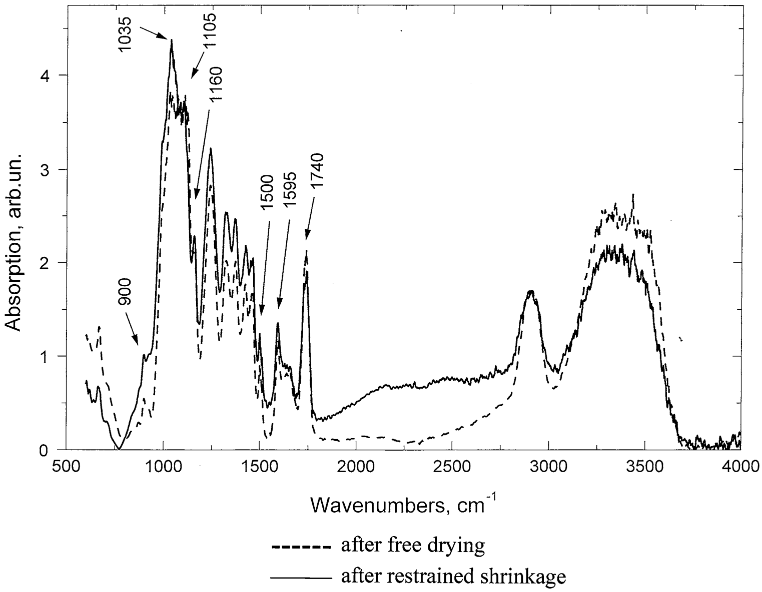


Fig. 11 IR absorption spectrum of birch wood

loaded wood, the degree of orientation in the amorphous area of cellulose increased (Fig. 11).

This phenomenon allows proposing an additional increase in wood stiffness. The hypothesis that this will lead to additional increase in wood stiffness was confirmed experimentally. Wetting in water and consequent drying returns the original wood nanostructure.

Strains at drying of loaded wood

Generalized results of a consequent research by Ugolev et al. (2009) on wood hygromechanical strains are shown in Fig. 12.

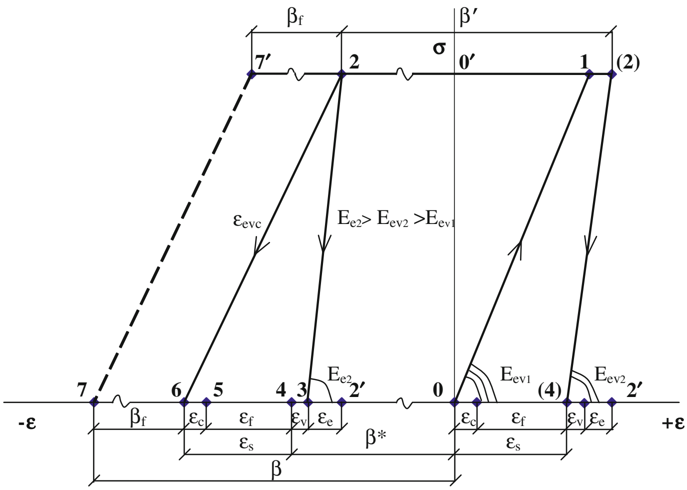


Fig. 12 Scheme of wood deforming perpendicular to grain at constant load, drying and unloading

Here, 0–1—tension of wet wood, 1–2—drying of loaded wood, 2–3–4—unloading and time of exposure of dry wood; sections: 0–4—“reduced shrinkage” β^*, 4–5—frozen elastic–viscous strain ε_f, 5–6—creep ε_c, 4–6—set-strain ε_s, 6–7—“frozen shrinkage” β_f, 0–7—free shrinkage β.

During wetting, shrinkage disappears and original size of the wood specimen is recovered.

Under tensile load perpendicular to grain, shrinkage decreases. The degree of the reduction in wood shrinkage increases with increasing tension stress. This reduction is especially appreciable when stress exceeds half of the tensile strength (Ugolev and Galkin 2008). Reduced shrinkage may be named hyposhrinkage of wood. Such phenomenon was observed by many researchers (Ohsako et al. 1968; Fujita 1982; etc.). Chulitsky (1938) was probably the first to detect an increase in shrinkage that is hypershrinkage of wood under compressive force.

Frozen mechanical strain and frozen shrinkage at drying fastened specimen

During drying, restraining of shrinkage may not only appear under tension by dead load, but as a result of self-loading of fastened specimens when initial size is constant. Deformative conversions occurring in this case have been investigated. Figure 13 shows the results of one of the experiments.

Adjusted method of calculating drying stresses in wood

To demonstrate the role of deformative conversions during the formation of drying stresses, results of the same experiment can be used (Fig. 13) in another interpretation.

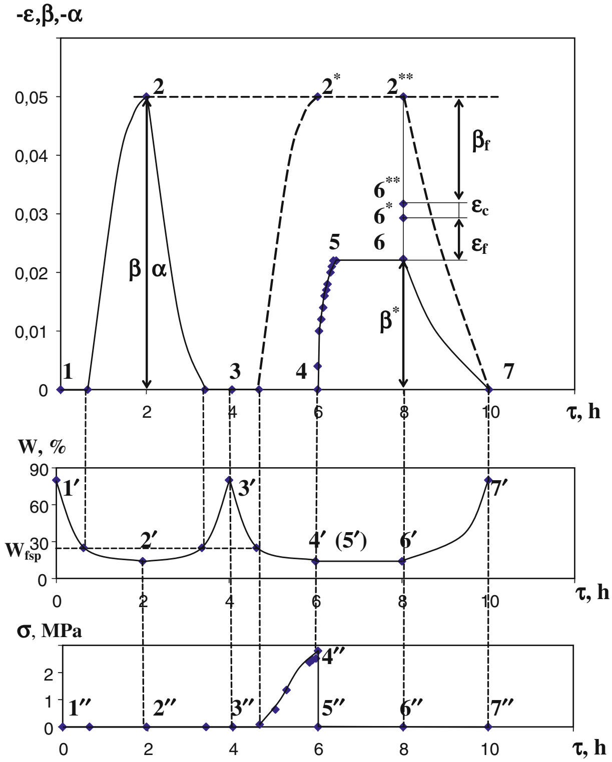


Fig. 13 Changing strains (ε), moisture content (w), stresses (σ) with time (τ) of experiment (ash, tangential direction, $t = 80$ °C)

Figure 14 shows that the restrained shrinkage of loaded wood β' includes "reduced shrinkage" β^* and set-strain, i.e., ε_f and ε_c. It is significantly less than free shrinkage β due to tensile load. Here, also the raising of stresses 1–2* is shown, which could have appeared if shrinkage coefficient K_β did not depend on loading. In this case, restrained shrinkage β' would be equal to free shrinkage β. The difference between supposed and real restrained shrinkages (β and β') is "frozen shrinkage" β_f. Thus, "frozen shrinkage" (FSh) decreases by the amount of σ the supposed calculated stresses (point 2*) to their real value (point 4).

$$\sigma = \sum_{i=1}^{n} K_{\beta_i}(\sigma) \Delta w_i E_i(w, t) \tag{7}$$

where σ, stress; i, step number; K_β, coefficient of shrinkage; Δw, moisture content drop from limit saturation of cell wall (FSP); E, stiffness modulus; t, temperature decreases from 100 °C; w, moisture content

"Mechano-sorptive creep" (MSC) plays the same role as FSh in calculations by Ranta-Maunus (1989), Moren (1993), Svensson and Toratti (2002), Pang (2005) and

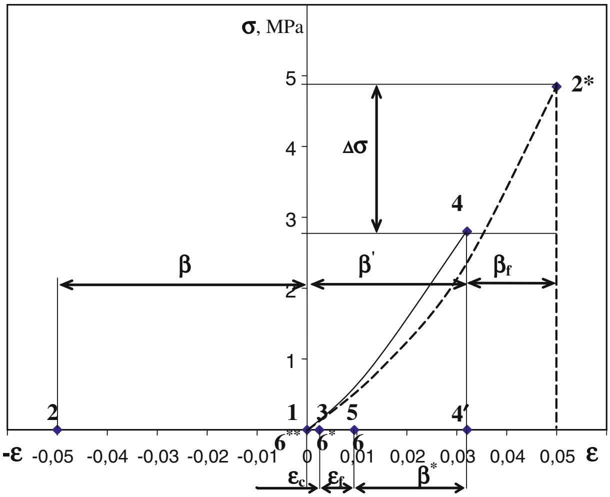


Fig. 14 Deformative conversions in wood at formation of drying stresses (ash, tangential direction, $t = 80$ °C)

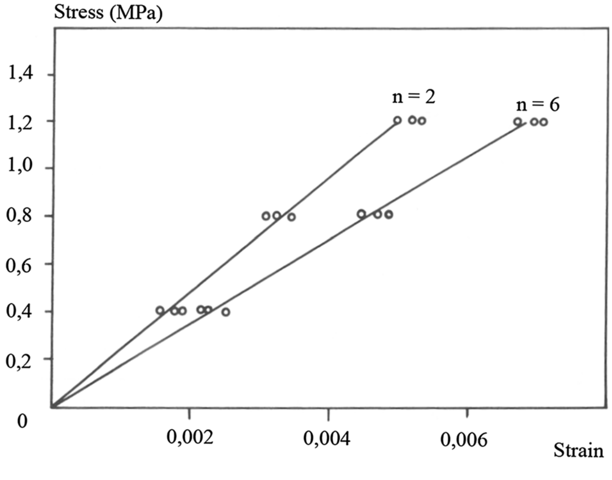


Fig. 15 Decrease of wood stiffness at hygrofatigue. *n*—number of sorption – desorption cycles: MC from 12 to 20 % (spruce, tangential direction)

other researchers. The MSC factor used in calculations should likely be replaced by the physically more approved term "frozen shrinkage."

Strains at cyclical moisture content and temperature changes of loaded wood

Mechano-sorptive creep can be observed at *cyclical* changes of moisture content in loaded wood. The pioneering work by Armstrong and Kingston (1960), detailed review by Grossman (1976) and subsequent papers (Bažant 1985; Molinski and Raczkowski 1986; Hanhijärvi and Hunt 1998; Toratti and Svensson 2000; Muzsynski et al. 2003 and others) was devoted to the research of this phenomenon both along and perpendicular to the grain of wood. MSC is used for interpretation of wood physical aging (Hunt and Gril 1996), calculation of internal stresses in glulam beams (Mirianon et al. 2008) and various other cases.

Studies in collaboration with L. Popovkina (Ugolev and Skuratov 1995) have shown that extraordinarily large strains arise from decreasing wood stiffness. This phenomenon was named hygrofatigue. It can be seen from Fig. 15 that even several moisture content cycles induce noticeable wood compliance raising growth. Erickson (1997) shares the opinion about the role of hygrofatigue in MSC. The strength loss due to hygrofatigue must be taken into account in lumber seasoning, wood building constructions, etc. It is very likely that the same phenomenon—thermofatigue exists at cyclical temperature changes.

Conclusion

Wood reveals manifold features typical for smart materials. Among them, effects of "strain memory" and "stress memory" have a dominant significance. Wood memory effects are based on "frozen strains." Frozen strains are the result of temporary reconstruction of wood nanostructure under controlled load influence in processes of drying or cooling. Frozen strains and other deformative conversions of loaded wood arise during drying, heat treatment, pressing, bending and maintenance of building designs.

Further investigations on deformative conversions of wood as elasto–visco-plastic material will allow for improvement of technology processes, effective use of wood and wood-based materials in sustainable constructions and creation of new and smart wood composites.

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