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Stress-strain state of wood at kiln drying *

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Summary. A model has been suggested which allows the calculation of stresses arising in kiln drying and humidification of wood, as well as the total residual strain, i.e. "set strain" ε_s, consisting of purely residual strain ε_r and the so-called "frozen strain" ε_f. Frozen strains arise under the operating influence of loading when the stiffness is increased because of a decrease in moisture content (or temperature) of the wood. The process of formation of set strains ε_s has been shown to depend on the history of loading, variations of the moisture content of the wood, as well as cooling of the section before the measurement of ε_s. The possibility of using set strain as a parameter of the state of stress of wood in kiln drying has been noted.

Introduction

Stresses cause checking, either on the surface or inside lumber as well as undesirable deformations of dried wood at the time of its machining. The interest in investigating the stresses at lumber drying originated long ago. Quantitative investigations in this direction were, however, initiated in the former USSR however only in early 50's (Ugolev 1952). The method of determining the residual stresses that was developed, was later used as the basis of the National Standard. At the present time, work is under way towards creating an ISO Standard. The suggested methods of measuring and predicting stresses in the process of drying based on a determination of elastic strains have been summarized in a monograph by Ugolev (1959). Investigations of the deformability of wood in the process of drying, which resulted in the experimental determination and theoretical substantiation of the effect of transformation of a part of elastic strains into quasi-residual ones, have been described in detail (Ugolev 1965, 1971). General laws of deformation of wood when loading is carried out under conditions of changing moisture content (or temperature), which take into account the above mentioned effect, were established. They allowed certain experimentally discovered phenomena (Helinska-Raczkowska, Raczkowski, 1977 etc.) and were used for developing methods of calculating drying stresses (Ugolev et al. 1980). Later, a generalized method was suggested for calculating stresses on drying and hygro-thermal treatment (Ugolev et al. 1986). Application of a temperature-moisture analogy and simulation

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of pure shrinkage by load-induced strains made it possible to establish experimentally the mechanism of frozen strains, and substantiate the effect of the "memory of wood" (Ugolev 1986). In the further development of methods for stress calculations (Ugolev 1987) the defreezing of strains was taken into account. Shrinkage of boards along width depends on the magnitude of stresses. It was suggested to use the differential shrinkage as a parameter for controlling the process of drying lumber (Ugolev et al. 1980; Trebula 1981; Hill, Lessard 1986; Limbert et al. 1987 etc.).

One of the components of shrinkage of board is the so-called "set" strain which has long been attracting attention of researchers (Koehler, Thelen 1926) together with casehardening. Set strains appearing on drying of a clamped wood specimen were determined by Ugolev (1965). Lately slice-by-slice set strains in drying of boards were investigated by Tokumoto (1989), who considers these strains to be the cause of the distinctive changes of stresses in drying of wood. The set strains, a considerable fraction of which is made up of frozen strains, are a consequence of development of stresses and increase in stiffness of wood in drying. The magnitude and the kinetics of change of "set" strains may be determined by making use of the model considered below.

Procedure

The model suggested is based on the fundamental laws of wood deformation under different conditions of loading. When wood is loaded under constant temperature and moisture conditions at a rate of 1×10^{-5} to 1×10^{-3} MPa/s, the relationship between stress σ and strain ε is given by the curve in Fig. 1, which may be replaced by a straight line without any significant error; the slope of this line corresponds to the modulus of elasticity E. The relationship between σ and ε in this case is analogous to Hook's law. The total strain ε_0 attained includes recoverable elastic–viscous strain ε_{ev} and unrecovered set strain ε_s which appears upon unloading. The line of unloading is characterized by modulus E, whose magnitude may be assumed to be approximately equal to $1.5 \times E$. Under these conditions the set strain equals the pure residual strain ε_r.

Tension – compression testing across the grain at various stable temperatures t and moisture contents of wood W gives the relationship $E = f(W, t)$ (Fig. 2).

Step by step loading of wood along with simultaneous raising of the modulus of elasticity by reducing the mositure content (or temperature) and subsequent unloading reveal the strain ε_r and the "frozen" strain ε_f (Fig. 3) The relationship between stress and strain in this case is expressed by the differential form of Hooke's law.

Similar testing with reduction of the modulus of elasticity by raising the moisture content (or temperature) results in the formation of unrecovered strain which in this particular case equals the strain ε_r (Fig. 4). Under these conditions, deformation of wood conforms to Hooke's law in its usual form.

The relationships which have been considered above along with the equations of moisture conductivity and moisture transfer were used for developing a method of calculating the stress-strain state of wood in drying and humidification processes (one-dimensional problem) (Ugolev et al. 1986).

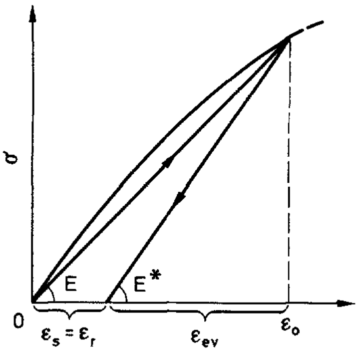

Fig. 1. Stress-strain relationship for loading and unloading at constant moisture content and temperature

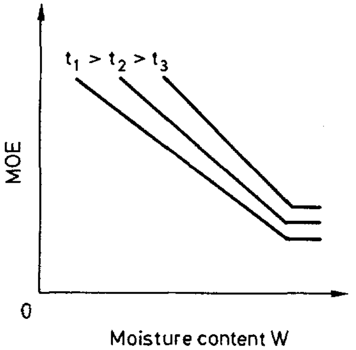

Fig. 2. Relationship between modulus of elasticity (MOE) and moisture content W at various temperatures

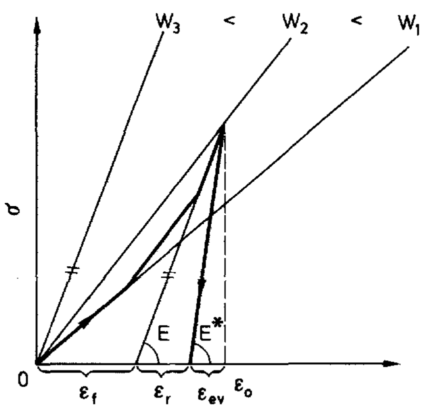

Fig. 3. Stress-strain relationship for loading and unloading during drying. W_1, W_2, W_3 moisture contents

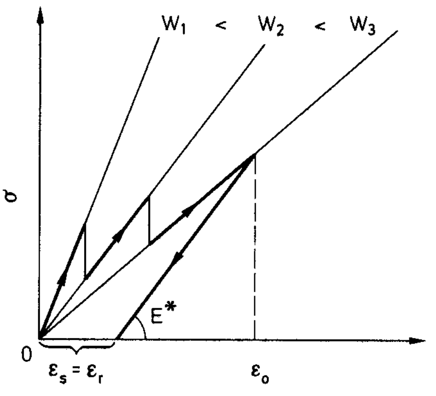

Fig. 4. Stress-strain relationship for loading and unloading during wetting. W_1, W_2, W_3 moisture contents

The following constitutive equation was used to calculate the stresses:

$$\sigma_{i'}^{j} = A_{i'}^{j}\,\sigma_{i'}^{j-1} + \alpha\, B_{i'}^{j}(\bar{W}_{i'}^{j} - \bar{W}_{i'}^{j-1}) - B_{i'}^{j}\left[\frac{\sum_{i=1}^{n} A_i^j \sigma_i^{j-1} + \alpha \sum_{i=1}^{n} B_i^j(\bar{W}_i^j - \bar{W}_i^{j-1})}{\sum_{i=1}^{n} B_i^j}\right]$$

where:

$A^j = 1$, $B^j = \bar{E}^j$ for drying and cooling,
$A^j = E^j/E^{j-1}$, $B^j = E^j$ for humidification,
E modulus of elasticity (MOE)
$\bar{E}^j = 0.5\,(E^j + E^{j-1})$ average modulus of elasticity,
W moisture content

$$\bar{W} = \begin{cases} W_{FSP} - W & \text{at} \quad W < W_{FSP} \\ 0 & \text{at} \quad W \geq W_{FSP} \end{cases}$$

α coefficient of shrinkage or swelling,
σ stress,
j step number,
i slice number,
n quantity of slices

The distribution of moisture content and temperature over the thickness was calculated by solving the differential equations of heat and mass transfer (Luikov 1978), using experimental data on physical properties of wood.

Application of the method made it possible to establish the basic relationships of development of the stress-strain state of wood when its moisture content and temperature are subject to change.

Results

The results of calculation of the stress-strain state of the 50 mm thick pine sapwood model of board are given below. The drying schedule used is given in Table 1.

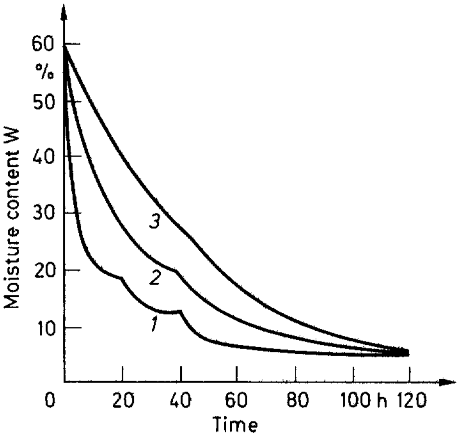

Fig. 5. Variation of moisture content W with time. *1* at the surface; *2* in intermediate, *3* in internal zones

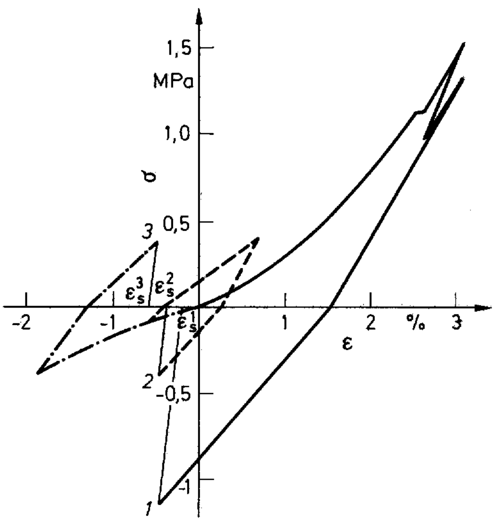

Fig. 6. Stress-strain relationship for *1* surface, *2* intermediate and *3* internal zones

Table 1. Drying schedule

Moisture content W, %	Temperature °C	Relative humidity of environment, %
60–35	73	80
35–25	77	66
25– 5	96	31

The initial moisture content of the board was 60% and the final one was 5%. The velocity of air flow relative to the material was assumed to be 2 m/s.

The curves showing the variation with time of the moisture content of different slices of the model in drying are shown in Fig. 5. The surface slice is 2.5 mm thick, the centre of the intermediate slice lies at a distance of 6.5 mm from the surface and that of the internal slice at a distance of 17.5 mm. The stress-strain relationship for the indicated zones of the model is given in Fig. 6. In the initial stage of the process, an intensive moisture removal occurs only from the surface slices in which significant tensile stresses are developed quite rapidly. During this period, the moisture content of the intermediate and internal slices remains practically unchanged, and the compressive stresses present in them are very small. Reduction of the growth of stresses in the surface zone is explained by the removal of bound water from the intermediate zone where tensile stresses begin to develop quite intensively. The subsequent jump of surface stresses is caused by the stepwise change of environmental parameters upon transition to the second stage of the drying schedule.

The moisture content of the surface slices rapidly falls to the equilibrium value while the moisture content of the intermediate zone continues to drop significantly, which leads to a further growth of tensile stresses and unloading of the surface slices. Transition to the third stage of drying schedule, due to a sharp rise of temperature and reduction of the environmental humidity, causes a brief, stepwise growth of surface stresses and a corresponding reduction of stresses in the intermediate zone. At the same time, stresses in the internal zone do not change significantly. At this point, substantial set strains accumulate in various slices of the board, the major portion of which is made up of "frozen" strains ε_f. The further course of the process is explained by the removal of bound water from the internal zone of the board, which causes a pronounced reduction of stresses along the thickness of the board and a subsequent reversal of their sign. The process of stress change is terminated upon equalization of the moisture content over the board cross section. When the process is terminated, all the slices of the board have the same strain equal to 0.5%. It is necessary to note that in a real board a strict equality of strains in all the slices is not obtained because of deformation of the edge of the board (differential shrinkage). In this way, compressive residual stresses appear in the surface zones of the board after drying and tensile stresses in the internal one.

The state of stress attained towards the end of the process results in a nonuniform distribution of set strains along the board thickness, which may be found after unloading of each slice (Fig. 6). This can be achieved by cutting the cross section of the board into slices. As can be seen from the above, the magnitude of "set" strain is determined by the history of development of the stress-strain state, which in its turn depends upon the physical-mechanical properties of the wood and the state of the environment. The pattern of variation with time of "set" strains in various slices of the model of the board is shown in Fig. 7 (curves 1, 2, 3). The conditions under which "set" strains are determined have a substantial bearing. The indicated curves have been plotted with the condition that unloading of all the slices occurs after cooling the sections to a temperature of 20 °C. Hence, the set strain to be determined includes not only the strains accumulated in the process of drying but also the frozen strains caused by cooling. Since the stiffness of the dried wood is sufficiently high, the portion of strain ε_f, within the set strain is quite substantial. The curve representing the variation

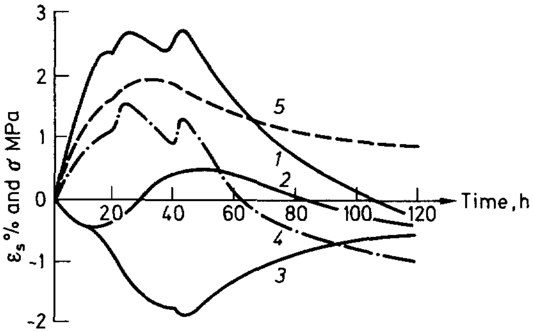

Fig. 7. Variation of set-strain versus time (after cooling). *1* at the surface, *2* in intermediate, *3* in internal zones, *4* stress and *5* (without cooling) at the surface

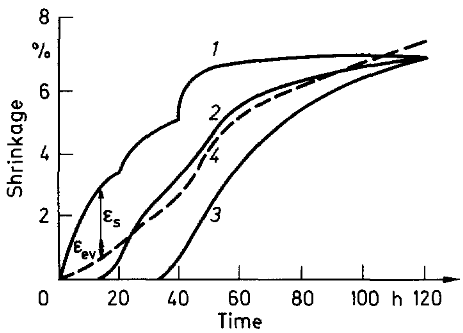

Fig. 8. Variation of shrinkage. *1* at the surface, *2* in intermediate and *3* in internal zones, *4* of the whole board, versus time

with time of "set" strain the surface slices which develop after unloading without cooling (curve 5) has also been given in Fig. 7. As can be seen from the graph, cooling exerts a considerable influence on the magnitude of "set" strains. It is obvious that the reversal of sign of ε_s, which has been noted (Tokumoto 1989), is associated with the circumstances indicated above.

A comparison of the curves showing the variation in the process of drying of "set" strains (curve 1) and stresses (curve 4) in the surface slices is of definite interest. The obvious similarity of variation of the indicated parameters provides a basis for supposing that set strain might be considered to be the governable parameter of the stress-strain state of wood in drying.

Figure 8 shows the pattern of variation with time of shrinkage in the surface, intermediate, and internal zones as well as that of shrinkage of the board i.e. the relative change in the board-model width. It is obvious that the curves of shrinkage of various slices of the model are determined by the variation of their moisture content. The magnitude of shrinkage of the board at each moment of time is a function of the stress-strain state. The difference between the magnitude of shrinkage of the board and the shrinkage of each slice equals its total strain. The relationship

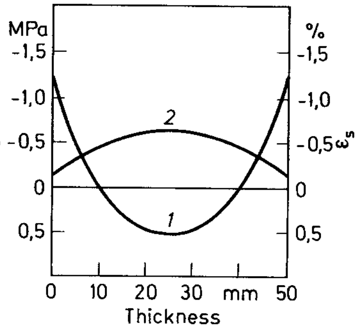

Fig. 9. Distribution of *1* residual stresses and *2* set-strains over the thickness after drying

between the components of total strain i.e. elastic-viscous strain and set strain, in the course of the whole process varies considerably.

The curves for distribution of residual stresses and set strains along the thickness of the board model, after the termination of the process of drying when all the slices have the same moisture content equal to 5%, are given in Fig. 9. The set strains for each slice have been determined with the condition that their unloading occurs after cooling to 20 °C of the section cut from the board. The characteristic feature of the distribution of set strains thus obtained is the fact that the strains ε_s for each slice have one and the same sign.

Conclusion

1. The model suggested makes it possible to evaluate quantitatively the stress-strain state of the board in the process of drying.

2. Formation of set-strains is a consequence of the history of loading of the wood in the process of drying.

3. A substantial portion of set-strains, which has been determined experimentally, is made up by the frozen strains which accumulate in the process of drying and cooling of the board cross section before unloading the slices by means of cutting the sections. The conditions of cooling of the section have a considerable bearing.

4. The curves of variation of stresses and set-strains in the process of drying are similar; this fact enables one to use set-strain as a governable parameter of the state of stress of the board, although this is coupled with the necessity of additionally determining the shrinkage of the board and the shrinkage of each slice.

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