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EFFECT OF "FREEZING" OF WOOD DEFORMATIONS AT COMPLEX FORCE AND HEAT ACTIONS

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The phenomenon of quasi-residual or frozen ability of wood to create deformations is considered. Results of experiments on deformations with heating or cooling and with or without loading of wood are presented.

INTRODUCTION

Itakura and Takumoto [4] presented in their paper rheological aspects in developing internal stresses creation during wood drying revealing residual deformations and methods of their investigations. Some transformations of greater part of elastic deformations into residual ones has been thoroughly studied in course of drying of fixed wood specimen [5]. Further, it has been stated that the formation of moisture-thermo-reversible deformations, that is quasi-residual deformations, appears not only during drying but during cooling of loaded specimens as well; nevertheless such deformations were not observed during moistening or heating. All these facts have had been the basis of establishing law of wood deformation, where history of both force and moisture heat effect has been taken into account [7, 8].

As both temperature and moisture content have a similar effect on wood stiffness, it is reasonable to use this similarity and investigate wood behaviour by drying, moistening and impregnating when studying combined effect of heat and force effect on wood deformation. It also has a self-effect in substantiation the processes of pressing, bending and modification of wood.

THEORETICAL RESEARCH

EFFECT OF "FROZEN" DEFORMATIONS ON WOOD STRESSES AT HEATING

Rheological tests of wood characterised by stable moisture content and temperature are characterized by exponential dependence under loading perpendicularly to the grain at fairly small rates between stresses and total deformations [6]. For simplification let us consider wood at constant moisture content to be linearly-elastic material that does not form residual deformations. In this case we have the following dependence between stresses, deformations and temperature:

$$\sigma=\varepsilon E_0(1+\gamma\Theta) \tag{1}$$

where σ represents stress, MPa; ε – deformation; E_0 – modulus of elasticity at $\Theta=0$°C, MPa; $\Theta=(100-t)$°C – temperature and γ coefficient, 1/°C.

Fig. 1 shows a diagram the "roof" of which – 0, 5, 9, 6 – is a family of lines revealing the dependence between stresses and deformations at various temperatures. If we cool down the wood heated up to 100°C to the temperature Θ_1 and load that wood (segment 1 - 2), then the deformation ε_1, corresponding to 1 - 2′ is formed. If we are further cooling down wood specimen to end temperature Θ_e, keeping the constant load, then the total deformation will not change: $\varepsilon=\varepsilon_e$ (segment 1 - 2′ is equal to 5 - 3′). Yet, meanwhile "frozen" deformations ε_f will be formed which in the final stage of cooling will characterize segment 5 - 4 out off on abscissa by unloading line 3 - 4 drawn at an angle corresponding to the modulus of elasticity E_e at end temperature.

The relationship between "frost" deformations and current temperature may be written as follows:

$$\varepsilon_f=\begin{cases} \dfrac{\varepsilon_1\gamma(\Theta-\Theta_1)}{1+\gamma\Theta} & \text{at } \Theta_1<\Theta\leqslant\Theta_e \\ & \text{at } 0<\Theta\leqslant\Theta_1 \\ 0 & \text{at } \Theta_e \end{cases} \tag{2}$$

If the wood is reheated without being unloaded at Θ_e, then the stress σ_R necessary to keep deformation at $\varepsilon_e=\varepsilon_1=$const. may be determined using the formula:

$$\sigma_R=E_\Theta(\varepsilon_1-\varepsilon_f) \tag{3}$$

where E_Θ is modulus of elasticity at the given temperature Θ. In Fig. 1 stresses σ_R remain constant in the (segment 3 - 2) because the reduction of E_Θ caused by a rise in temperature is compensated by an increase of elastic deformations $(\varepsilon_1-\varepsilon_f)$. In accordance with (2) at further rise in temperature, the deformation $\varepsilon_f=0$ and in the segment 2 - 6 at $\varepsilon_0=\varepsilon_1=$const. stress relaxation σ_R takes place caused by the decrease of E_Θ. Wood has "memorised" the temperature Θ_1 at which its loading has taken place. If we unload wood at Θ_e and keep $\varepsilon'=$const., then stresses σ_r will appear, that can be derived according to:

$$\sigma_r=E_\Theta(\varepsilon'-\varepsilon_f) \tag{4}$$

In Fig. 1 the segment 4 - 7 shows an increase in stresses resulting from retardation of the recovery, while the segment 7 - 8 shows the stress relaxation. And again we can conclude that the wood has "memorised" the temperature of the initial loading.

At multi-step loading and cooling down the equation of the "frozen" deformation may be written as follows:

$$\varepsilon_f=[\gamma(\Theta\sum_{i=0}^{n}\varepsilon_i-\sum_{i=0}^{n}\varepsilon_i\Theta_i)]/(1+\gamma\Theta) \tag{5}$$

where Θ is current temperature and Θ_i is the temperature of the loading step.

If the wood is continuously loaded and cooled down at

$$\varepsilon=\alpha\Theta \tag{6}$$

where α is the coefficient, then the "frozen" deformation may be derived from the following equation:

$$\varepsilon_f=0.5\gamma\Theta^2/(1+\gamma\Theta) \tag{7}$$

If we extend previously obtained dependence [7, 8] of stresses from retarded shrinkage to continuous loading and cooling, then the equation will bee as follows:

$$\sigma=\alpha\Theta E_0(1+0.5\gamma\Theta) \tag{8}$$

In Fig; 2 segment 1 - 2 shows changes in stresses σ, and segment 2 - 3 shows those of σ_R at ε_0=const. These stresses σ_R can be derived from the following equation:

$$\sigma_R=E_0[\varepsilon_0(1+\gamma\Theta)-0.5\alpha\gamma\Theta^2] \tag{9}$$

Stresses due to retarded recovery (segment 4 - 5) can be derived from the equation:

$$\sigma_r=0.5\,[\alpha\gamma E_0(\Theta_e-\Theta)(\gamma\Theta_e\Theta+\Theta_e+\Theta)/(1+\gamma\Theta_e) \tag{10}$$

Maximum value of these stresses equal to

$$\sigma_{r\max}=0.125\,[\alpha\gamma E_0\,\Theta_e^2(2+\gamma\Theta_e)^2/(1+\gamma\Theta_e)^2 \tag{11}$$

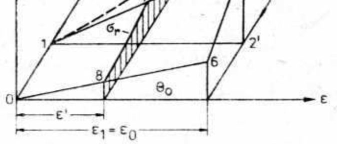

Fig. 1. Changes in stresses at heating after single-step loading and cooling

Rys. 1. Zmiany naprężeń przy ogrzewaniu po jednostopniowym obciążeniu i ochłodzeniu

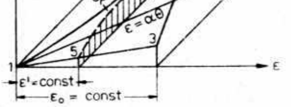

Fig. 2. Changes in stresses at heating after contihous loading and cooling

Rys. 2. Zmiany naprężeń przy ogrzewaniu po ciągłym obciążeniu i chłodzeniu

is obtained at critical temperature:

$$\Theta_e=0.5\gamma\Theta_e^2/(1+\gamma\Theta_e) \tag{12}$$

SIMULATION OF WOOD BEHAVIOUR DURING DRYING AND MOISTURE-HEAT-TREATMENT

Below we shall consider several possible combinations of force and heat effects on wood [10]. Let us assume that the tension of beforehand cooled wood takes place at constant temperature $\boldsymbol{\Theta_e}$ **(Fig. 3, straight line 0 - 1)** and unloading with simultaneous heating from Θ_e to Θ_0 at $\varepsilon=\alpha\Theta$ (curve 1 - 0); then stresses during loading may be derived from the equation:

$$\sigma=\varepsilon E_e=\varepsilon E_0(1+\gamma\Theta_e) \tag{13}$$

and those during unloading may be obtained in accordance with the equation:

$$\sigma=\varepsilon E_\theta=\alpha\Theta E_0(1+\gamma\Theta) \tag{14}$$

In order to obtain the same deformation $\varepsilon=\alpha\Theta_e$ the wood may be loaded when cooled from Θ_0 to Θ_e. In this case smaller stresses will be needed, as a part of elastic deformations will be transformed into "frozen" ones. The stresses may be derived from equation (8). The same equation allows to obtain the relationship between stresses and deformations at the next stage of unloading with heating in the course of which thawing of deformations takes place. Dependences similar to that described above are typical of the behaviour of surface zone of wood at the initial stage of drying and at intermediate moisture-heat-treatment.

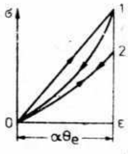

Fig. 3. Relationship between stresses and deformations during unloading with heating

Rys. 3. Zależność między naprężeniami i odkształcenia w czasie odciążania z ogrzewaniem

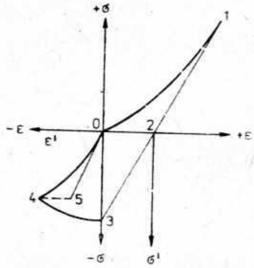

Fig. 4. Behaviour of the surface zone of a board during drying and final moisture-heat treatment

Rys. 4. Zachowanie się strefy powierzchniowej deski w czasie suszenia i ostatecznej obróbki wilgotnościowo-cieplnej

Simulation of the whole cycle "drying – final moisture-heat treatment" allows to obtain dependences shown in Fig. 4. Substituting in the equation (8) and further the temperature Θ for the moisture decrease w, which equals to

$$w=w_s-w \tag{15}$$

where w_s is saturation limit of cell walls, we can get the equation for determining stresses σ_{0-1} at the stage of drying surface zone of a board (Fig. 4, 0 - 1). At the unloaded stage in this zone (due to the internal zone shrinkage), the stresses will change in accordance with the law for the straight line 1 - 2. Stresses in this segment at total delayed deformation $\varepsilon_d=\alpha w_d$ may be derived according to the equation:

$$\sigma_{1-2}=E_e(\varepsilon_d-\varepsilon_{fe})=\alpha E_e[w_d-0.5\gamma w^2/(1+\gamma w_e)] \tag{16}$$

"Frozen" deformation at the end of drying $\varepsilon_{f.e}$ corresponds to the segment 0 - 2. Point 2 characterizes the state, when moisture in internal zone is higher than that in surface zone. Therefore let us place the beginning of coordinates in point 2 and consider a change in compression stresses in the system of coordinates $\sigma' - \varepsilon'$. In the segment 2 - 3 stresses will increase so that in point 3 (at identical moisture content both in internal and surface zones) they will be equal to:

$$\sigma_3 = \varepsilon_{f.e} E_e \tag{17}$$

Thus elastic deformations of compression have completely compensated "frozen" deformations developing due to tension. Subsequent restrained swelling of wood at the stage of moistening during moisture-heat-treatment leads to the formation of compression stresses:

$$\sigma_{3-4} = \alpha E_w [0.5 w_e (3 - E_0/E_e) - w] \tag{18}$$

Stresses at the stage of subdrying segment 4 - 0 can be derived in accordance with the equation:

$$\sigma_{4-0} = 0.5\alpha\, [E_m (2w_e - w_m - w_e E_0/E_e) + E_e (w_m - w_e)] \tag{19}$$

where E_M is the modulus of elasticity at the end of moistening stage.

The equation to determine moisture content (in point 4) up to which it is necessary to moisten the wood so that the stresses were reduced to null as a result of subsequent subdrying, wo can obtain from the following formula:

$$w_m = w_e [(3E_e - E_0)/2E_e - \sqrt{(5E_e^2 - 2E_e E_0^2)/4E_e^2}] \tag{20}$$

During subdrying "frozen" deformations will again develop, the value of them will correspond to the segment 4 - 5 by the end of this stage.

EXPERIMENTAL STUDIES AND DISCUSSION OF THE RESULTS

To check up predictions of wood behaviour at heat and force actions shown in Fig. 1 experiments have been carried on wood, the moisture content of which exceeds W_s.

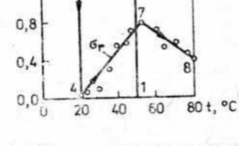

Fig. 5. Effect of temperature on stresses σ_R at constant deformation of wood ε_1

Rys. 5. Wpływ temperatury na naprężenia σ_R przy stałym odkształceniu drewna ε_1

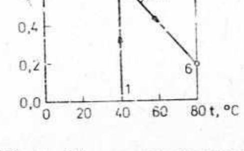

Fig. 6. Effect of temperature on stresses σ_r at constant deformation of wood ε'

Rys. 6. Wpływ temperatury na naprężenia σ_r przy stałym odkształceniu drewna ε'

In Fig. 5 results of experiments for compression perpendicular to the grain in Siberian pine (*Pinus sibirica*) at $\varepsilon_1=0.009$ have been shown. In Fig. 6 results of experiments with white oak (*Quercus robur*) at $\varepsilon'=0.007$ are presented. Both examples show that the wood has really "memorized" the temperature (40° and 50°C) of initial loading. The experiment carried out together with **Ščedrina** are confirming not the relationships of (2) ... (8) for single- and multi-stepped loading but also equations (9) ... (12) for continuous loading with cooling [9]. Main statements of the theoretical analyses presented in subsection of theoretical research concerning effects of "frozen" deformation on wood stresses at heating – confirms experimental data of other scientists [1, 2].

Theoretical statements discussed in the next subsection of concerning simulation of wood behaviour during drying and moisture-heat treatment have also been checked experimentally [3]. As an example we can see in Fig. 7 results of an experiment of tension perpendicular to the grain in an oak specimen. As it can be well seen the relationships [13] and [14] have been confirmed; lines of loading and unloading are different. Fig. 8 shows the results of an experiment in tension with cooling and unloading with heating in a scots pine specimen (*Pinus silvestris*). In this case, as in clearly seen in equation [8] the lines for loading and unloading coincide. Experimental confirmations of the regularities of other positions as well that stresses the development of computation methods for stresses at drying and moisture-heat-treatment of wood performed with the use of computers, have also been obtained.

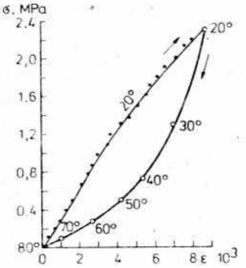

Fig. 7. Stress changes at loading of unheated wood and subsequent unloading with heating

Rys. 7. Zmiany naprężenia przy obciążaniu nie ogrzewanego drewna i dalszym odciążaniu z ogrzewaniem

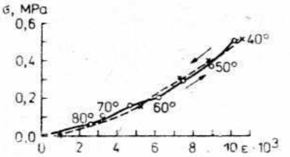

Fig. 8. Stress changes at loading with cooling unloading with heating

Rys. 8. Zmiany naprężenia przy obciążaniu z chłodzeniem i odciążaniu z ogrzewaniem

CONCLUSIONS

As a result of carried out investigations the ability of wood to form quasi-residual "frozen" deformations during the steering effect of loading at cooling (or drying) has been shown. These deformations are caused by temporary rearrangement in fine structure of the wood. They are recovered during heating (or moistening).

"Frozen" deformations are displayed in memory effect of the wood: it memorizes combined heat (moisture) and force actions. The formation of "frozen" deformations must be taken into account at developing computation methods for stresses in various processes of hydro-thermal treatment and modification of wood.

Praca wpłynęła do Redakcji
w listopadzie 1986 r.

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ЭФФЕКТ „ЗАМОРОЖЕНИЯ" ДЕФОРМАЦИЙ ДРЕВЕСИНЫ ПРИ КОМПЛЕКСНОМ СИЛОВОМ И ТЕМПЕРАТУРНО-ВЛАЖНОСТНОМ ВОЗДЕЙСТВИИ

Резюме

В докладе приведены результаты теоретического и экспериментального исследования „замороженных" деформаций, возникающих в древесине при управляющем воздействии нагрузки в процессах охлаждения (или сушки). „Замороженные" деформации объясняют эффект „памяти" древесины на комплексные силовые и температурно-влажностные воздействия. На основе температурно-влажностной аналогии показана возможность моделирования и расчета поведения древесины при сушке и влаготеплообработках. Результаты исследования имеют также значение для обоснования процессов прессования, гнутья, модифицирования древесины.

EFEKT „ZAMROŻENIA" ODKSZTAŁCEŃ DREWNA PRZY JEDNOCZESNYM OBCIĄŻANIU I OGRZEWANIU

Streszczenie

Przedstawiono wyniki rozważań teoretycznych i doświadczeń nad zjawiskiem „zamrożenia" odkształceń, wywołanych w drewnie podczas obciążania, przy jednoczesnym studzeniu lub ogrzewaniu. „Zamrożone" odkształcenia wyjaśniają efekt „pamięci" drewna w przypadku kompleksowo działających obciążeń oraz czynników cieplno-wilgotnościowych. Na podstawie analogii temperaturowo-wilgotnościowej wykazano możliwość modelowania i przewidywania zachowania się drewna podczas suszenia i obróbki hydrotermicznej. Wyniki mają ponadto znaczenie dla ustalenia podstaw procesów prasowania, gięcia oraz modyfikacji drewna.

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