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TEMPERATURE-TIME CHARACTERISTICS OF WOOD STRENGTH

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The state of wood that is softened by bound moisture under normal weather conditions is the result of its demonstrated hygroscopic behaviour. The general equation for the long-term strength of solid bodies [3, 12]

$$\lg t = \lg A - \frac{\gamma\sigma}{RT} \qquad (1)$$

(where R – gas constant; A – temperature function) can be applied to wood only after introducing to this equation, besides stress σ, time t and temperature T, an additional parameter – the content of bound moisture w, %; this parameter is part of coefficient γ [6, 7]. The characteristic of wood strength can be demonstrated by a stereogram of the coordinates of $\sigma - w - T$ (where t is the duration of the machine test reduced to continuous action [2]).

By way of an example, Fig. 1,b shows the diagram for compression along the grain of oak wood. Initial data is derived from [1], but mean curves $\sigma_{br}(T)$ are plotted closer to the centres of point clusters, as shown in Fig. 1,a for sufficiently swollen specimens of wood (in a water-saturated state with a moisture content of 60%), i.e., with the content of bound moisture w = 30% with confidence interval ±3.73% at the confidence factor of 0.95 (curve *2*).

The same approach was used for plotting the mean straight line *1* for w = 0 (i.e., for absolutely dry wood) with confidence interval ±1.61%. If we extend the straight line *1* from axis *0T* (Fig. 1,c), we find the value of temperature T_v = 335±5.4 ºC. This temperature corresponds to the theoretical temperature range T_v of pulp vitrification between 220º and 370º, as identified in [9]. For wood that is softened by bound moisture, i.e., with $w > 0$, the mean curves based on the experimental data from [1] tend asymptotically towards the plane of $w - 0 - T$ (Fig. 1,b).

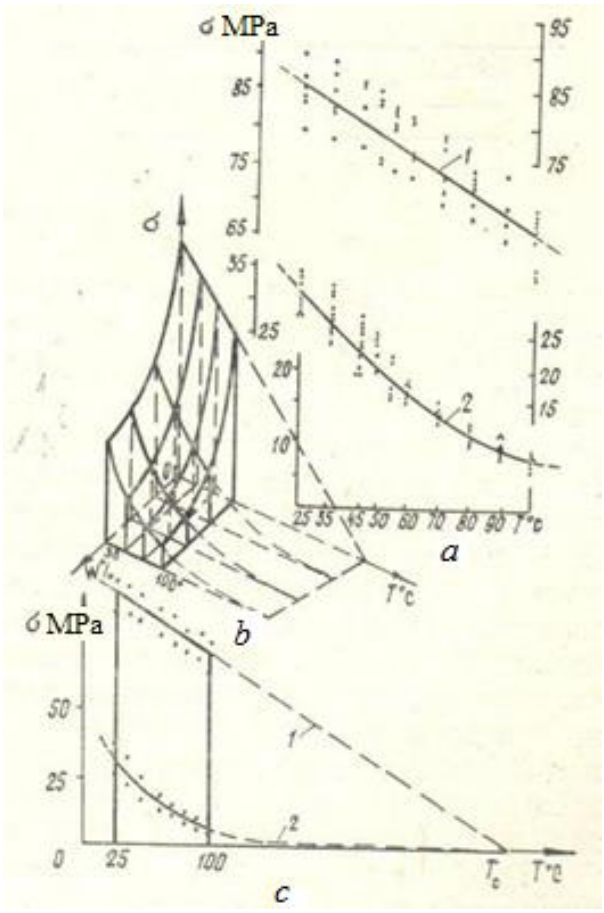

Fig. 1. Stereogram of the temperature-time characteristics of wood strength (*b*); plotting of the mean straight line (at w = 0) and curve (at w = 30%) based on experimental data of [1] (*a*); extrapolation of the straight line to theoretical pulp vitrification temperature (*c*).

At any constant temperature T_i = const, we see a hyperbolic curve on the plane $\sigma - 0 - w$ of the diagram (Fig. 1,b) for the function of $\sigma_{br}(w)$. If we take $0 - \lg t$ as the third axis (Fig. 2,a), we obtain a projection on the plane $\sigma - 0 - \lg t$ of a cluster with parallel beams for each value of bound water content w with the pole on the axis $0 - \lg t$ (the horizontal coordinate of the pole $\lg t = \lg A$ = 17.1 at 18°C), as was previously described in [4]. Let us look at the beam cluster on this plane in more detail.

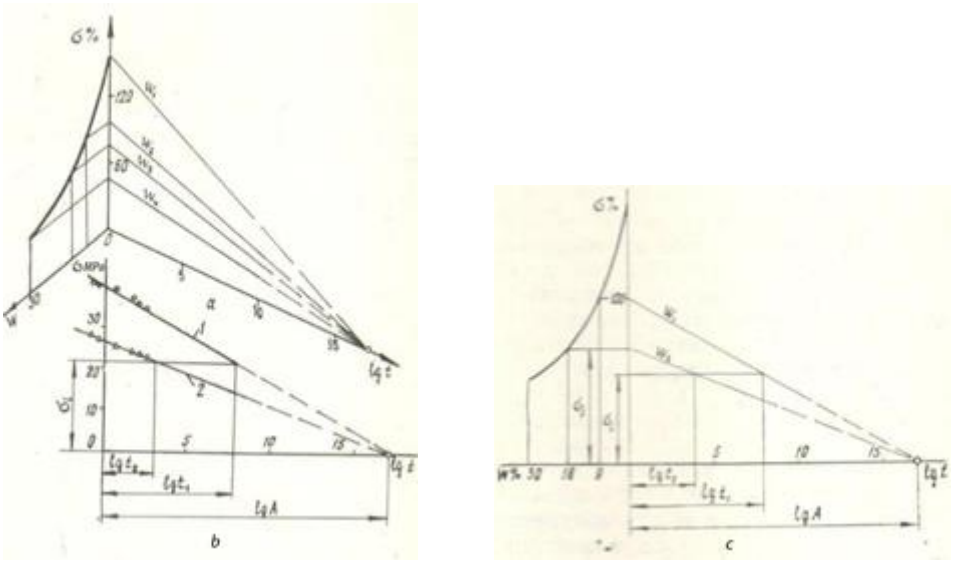

Fig. 2. Modelling of long-term wood strength at T_i = const.
Chart *a* – projection of long-term wood strength on the plane σ – 0 – lg *t*; *b* – an experimental cluster σ (lg *t*) for different moisture content values *w*; *c* – graphical determination of modelling conditions as taken for neutralised values of the strength of oak and pine wood during compression and tension perpendicular to the grain

By way of an example, Fig. 2,b demonstrates the results (mean for 10–12 specimens) of tests by compression along the grain of pine wood with two different values of moisture content *w* (15% and 30%), in a wide range of loading rates [10, 11]; the test points match the beams within narrow confidence intervals of ±2.10% and ±2.04%, respectively, with a confidence factor of 0.95 [8]. The same beams were obtained as a result of bending tests on pine wood with the same moisture content at different loading rates [10, 11] in a slower test [8] with confidence intervals of ±3.89% and ±1.22%, respectively.

The charts in Fig. 2,b show that, if specimens of wood with different moisture content values w_2 = 30% (line *2*) and w_1 = 15% (line *1*) are exposed to continuous stress σ_i = 21.6 MPa until rupture, the mean time to rupture t_2 for higher moisture content w_2 is smaller than the time for smaller moisture content w_1 (lg t_2 = 2.95, t_2 = 15 min; lg t_1 = 7.80, t_1 = 2 years). This means that, by increasing the content of bound moisture in the wood of tested specimens, we can reduce their mean time to rupture. This brings us to the important conclusion that modelling of long-term wood strength is a practical possibility. And while the established characteristics fully answer most questions of using the wood under continuous load, modelling of long-term strength should be used in some complicated cases of wood performance (complex stressed states, etc.).

To formulate the modelling conditions in analytical form, we must bear in mind, in addition to the normal equation (1) with constant coefficient γ, the influence of softening of wood by its bound moisture, as mentioned above. This influence is determined by the variation of coefficient γ with respect to bound moisture content *w*, % and temperature *T* [7]:

$$\gamma(\omega; T) = \gamma(\omega)_{\omega=0}[1 + \frac{\omega}{f(T)}], \qquad (2)$$

where *f(T)* is the ae^{bT} function of temperature (here, *T*K).

With constant stress σ = const, we can use equation (1) to obtain the general equation for modelling long-term wood strength, as follows:

$$\lg t_2 = \lg A_2 - \frac{\gamma_2 T_1}{\gamma_1 T_2}(\lg A_1 - \lg t_1), \qquad (3)$$

where t_1 – time to rupture to be modelled, with given T_1 and $\gamma_1(w_1; T_1)$;

t_2 – modelling time, with given T_2 and $\gamma_2(w_2; T_2)$; lg A_1 and lg A_2 at T_1 and T_2, respectively; γ_1 and γ_2 according to (2).

Whereas modelling should be carried out under the temperature at which a specific product will be in service for a long time, the temperature may be considered to be constant, with the only

variable represented by the content of bound moisture. This simplifies modelling equation (3) as follows:

$$\lg t_2 = \frac{\gamma_2}{\gamma_1}\lg t_1 - \lg A\,(\frac{\gamma_2}{\gamma_1} - 1). \quad (4)$$

Knowing the values of σ_i and the logarithm of the mean time to rupture lg t_1, we can graphically find the desired shortened time t_2, whose logarithm is cut out on the straight line $\sigma = \sigma_i$ by the beam for w_2.

Let us look at an example. Fig. 2,c shows a neutralised (% of σ_{br} at w = 9% and 20ºC) dependence σ_{br} (w) for the wood of oak and pine during compression along the grain and for the pine wood during tension perpendicular to the grain [7]. With a continuous stress σ_i = 53%, the mean time to rupture t_1 is 2.5 years and lg t_1 = 7.90. By setting the duration of experimental modelling in a laboratory environment for exposing the specimens to the same stress, but at w_2 = x% during the mean time to rupture t_2 = 1.5 hours and lg t_2 = 3.73, we will find the beam that cuts out the straight line at σ_i = 53%, lg t_2 = 3.73; we then plot the beam to the vertical axis (for the specified time t = 1 from the machine test where we determined σ_{br}, i.e. $t_1' \approx 38$ sec) and move the obtained vertical coordinate σ_j = 69% to the hyperbolic curve (Fig. 2,c), from which we calculate w_2 = 18%. Thus, exposing the specimens during the mean time t_2 = 1.5 hours under constant load σ_i = 53% (from σ_{br} = 9%) with the bound wood moisture content w_2 = 18%, we can model the mean time to rupture t_1 = 2.5 years for the same specimens and under the same stress but with w_1 = 9%. Naturally, when determining the number of specimens, we should consider a very wide range of individual values of t_2.

The question is this: will the influence of induced high-elasticity (IHE) strain [5] on the distribution of stress in the tested specimen differ during the modelling process from the natural conditions of long-time action of stress? This question falls into two parts: does the IHE strain occur after the limit of induced high elasticity σ_{he} of wood is exceeded and what is the rate of its development? Occurrence of induced high-elasticity strain is a process associated with that of accumulation of faults defining the time to rupture. If we accelerate the latter process (during modelling, for example, by increasing the bound moisture content), the former will accelerate automatically. As for the rate of IHE strain, existing data shows that an increase in the content of bound moisture of wood makes the rate of straining beyond the σ_{he} limit somewhat higher than in air-dried wood; this difference is determined by the ratio of w_1 and w_2 and, if the value of this ratio is small, it has no major effect on the modelling precision.

The described modelling principles also apply to large-scale tests, for example, water resistance tests of glued wood compounds. From the above perspective, machine testing of specimens of glued compounds of water-saturated wood (after exposure under water) is, in fact, modelling of strength behaviour of the wood under the conditions of its performance under load in layers adjacent to the adhesive interlayer essentially defining the strength of the compound. If, during the machine test at w_1 = 30%, the time to rupture (reduced to constant action of σ_{br}) t_2 = 0.78 sec and lg t_2 = −0.108, then the mean time to rupture for the same specimen in an air-dried state with, for example, w_1 = 12%, will be t_1 = 4 hours under continuous exposure to stress σ_{br}. Testing of specimens in a water-saturated state has the following physical value: it helps simulate the behaviour of specimens over a longer period of performance under load, which is essential for forecasting the long-term strength of glued compounds.

Yet four hours is too short a time to make any conclusions concerning the long-term performance of wood in compounds. These tests can easily be made ultimately effective for the purpose of forecasting if we expose the same specimen to continuous load in a water-saturated state and achieve rupture by shearing on average, for example, after t_2 = 3 hours (without considering the pulling stresses). Then we can simulate a longer mean time to rupture t_1 of ½ years.

As we can see, experimental modelling of long-term wood strength makes a difference not only in complicated cases of wood's performance as a material; it also offers brand new opportunities for finding the actual physical meaning of empirically formulated and widely practised types of large-scale test of wood compounds, such as glued compounds of wood.

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