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THE PARADOX OF WOOD BENDING RESISTANCE

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The paradox is defined as the decrease in wood strength σ_{br} after a certain loading rate is exceeded during wood machine test that is inverse to the normal increase in the strength of materials with the increase in load growth rate [5]. The deviation of vertical axes of σ_{br} downward from the straight line of lg *t* (δ) built for a slower loading was found during the bending tests (Fig. 1,a) with standard wood specimens (sized 20×20×300 mm) and confirmed by the results of timber tests (sized 50×152 mm, length 3.6 m, Fig. 1,b) carried out in Canada [10], as described in [5].

An adequate assessment of the wood strength through machine tests requires investigation of the mechanism of the paradox that has the following features: it manifests itself after a certain loading rate is exceeded, hence a certain rate of marginal strain $\dot{\varepsilon}_{mrg}$; this rate goes down as the depth of cross-section of a bending element increases; in wood with high moisture content (w = 30%), the rate that corresponds to the display of the paradox is higher than in air-dried wood (w = 15%) [5].

Bearing this in mind, we may presume that, in the marginal compressed grains of an element's cross-section, as soon as the stress σ_a in such grains transcends the limit of induced high elasticity σ_{he} of wood, i.e., when $\sigma_a > \sigma_{he}$, induced high elasticity strain $\dot{\varepsilon}_{ihe}$ will occur. After the occurrence of strain ε_{ihe} whose development rate is very high because it increases exponentially with stress (Fig. 2), development of marginal strain ε_{mrg} cannot follow, since it manifests itself under the law of plane sections through the strain of elastic core throughout most of the element's section; this creates the conditions for stress relaxation $\dot{\varepsilon}_{mrg} < \dot{\varepsilon}_{ihe}$.

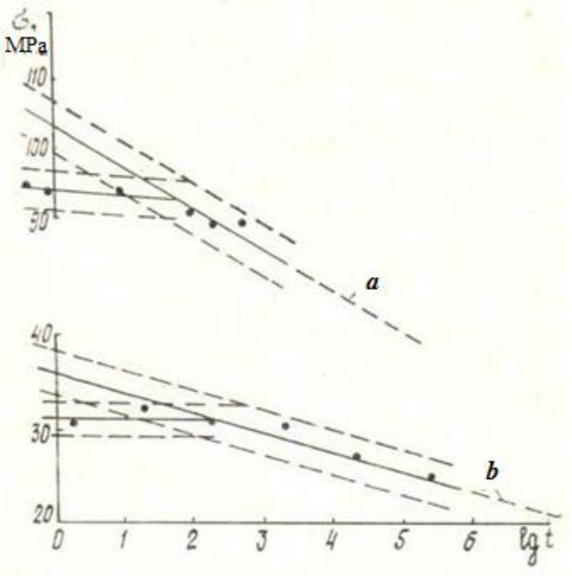

Fig. 1. Results of bending tests at different loading rates: *a* – standard specimens of pine wood (moisture content w = 15%); *b* – hemlock timber, grade 2, w = 8…13%.

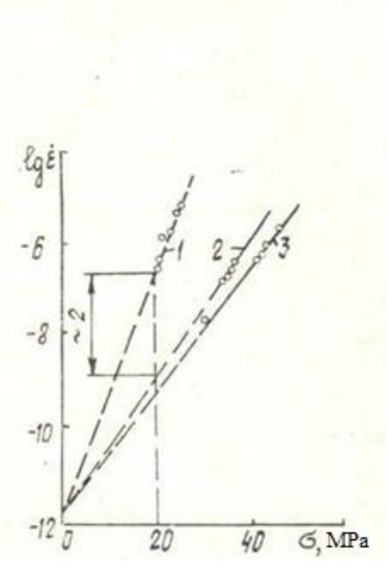

Fig. 2. Finding the lg of $\dot{\varepsilon}_{ihe}$ strain rate as a function of stress during experiments with compression perpendicular to the grains of beechwood: σ = const; w = 30% (1), 12% (2) and 8% (3); temperature ~ 20.7ºC.

Under continuous load, the bending elements demonstrate a significant increment in buckling [7] and, consequently, marginal strain; in this case, relaxation may develop in full, meaning that equation $\sigma_a \leq \sigma_{he}$ will be satisfied. This is confirmed by the proximity of test points to the straight line of lg t (σ) of long-term wood strength during bending tests with continuous loading on the specimens that had different cross-section dimensions. If the loading rate during machine testing increases rapidly with the corresponding increase in the rate of marginal strain $\dot{\varepsilon}_{mrg}$, stress relaxation does not have time to develop in the marginal compressed grains and the difference $\dot{\varepsilon}_{ihe} - \dot{\varepsilon}_{mrg}$ decreases, which leads to a reduction in the time until rupture and deviation of point σ_{br} downward from the straight line of lg t (σ) of long-term wood strength (Fig. 1), i.e., to the paradox phenomenon.

So the paradox occurs in the event of delay in stress relaxation due to the constrained development of strain ε_{ihe}. This strain needs time to develop. As a consequence, strain ε_{ihe} has no time at all to develop under the influence of a suddenly applied load and only elastic deformation occurs, due to which the paradox does not manifest itself. This resembles the dynamic (mechanical) vitrification of polymer, when the high rate of force action transfers the polymer (without reducing the temperature) from the domain of high elasticity straining to the domain of induced high elasticity strain ([6], pages 106 and 182). Polymer composite (wood) with a highly-oriented component, i.e., natural cellulose pulp, is transferred at high rates of mechanical action (impact) from the domain of nonlinear strain ε_{ihe} to that of linear elastic straining.

An increase in the combined moisture content w (%) causes the rate of $\dot{\varepsilon}_{ihe}$ grow rapidly; for example, when w increases from 12% to 30% and stress remains unchanged, the $\dot{\varepsilon}_{ihe}$ goes up by more than two orders of magnitude (for $\sigma = 20$ MPa and temperature of 293K, Fig. 2 [4]). This is why, in wet wood, the bending paradox must occur at higher test loading rates and with a lower deviation of σ_{br} downward from the straight line of lg t (σ) than that of air-dried wood, which is observed in the experiment [5]. As a result, the ratio of σ_{br} for air-dried wood versus σ_{br} for the same kind of fresh wood must be smaller than given compression along the grain, meaning that this ratio can numerically prove the above explanation of the paradox phenomenon.

This proof can be found in the results of wide-scale tests of different wood species in the USSR and the USA (see Table 1, where $\bar{X}$ – mathematical expectation, S – mean square deviation, and v – variation coefficient, %), because the value of lg t for these tests (see Table 2) lies within the range of lg t values for paradox occurrence:[*] based on the results of standard tests in the USSR, as shown in Fig. 1,a, $1.7 > -0.252$; based on the USA test results, the lower limit of the specified range of lg $t > 1.7$ (because the depth of cross-section of the specimens is $50.8 > 20$ mm), thus obviously higher than 1.01, as indicated in Table 2.

The paradox obviously occurs owing to a smaller influence of moisture content on the σ_{br} of bending compared to the compression along the grain, which is observed in the event of loading rate tests of timber. The explanation of this phenomenon by a smaller influence of moisture content on the resistance of wood to tension along the grain is disproved by the fact that rupture of timber at the knots in the tension area occurs almost universally as a result of fissure at an angle to the grains in the near-knot area and the influence of moisture content on this type of resistance is smaller than on the strength during compression along the grain.

Consequently, the data provided serves to corroborate the suggested explanation of the paradox mechanism by the delay in stress relaxation in marginal compressed grains of the bending element [5].

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[*] Time before rupture t is determined based on the test duration t'_1 using the equation $t = t'_1 / 2.3\,(\lg A - \lg t)$ [5], which is solved by successive approximation.

Table 1

Ratios of σ_{br} for air-dried wood and σ_{br} for fresh (wet) wood during compression and bending

Wood species	Type of test	Wood moisture content, %	Number of mean values of σ_{br}	Mean value of σ_{br}, MPa		Statistical parameters of the ratio σ_{br}(air-dried) / σ_{br}(wet)			Statistical assessment of difference $t_{0.05} = \frac{(\bar{X}_1 - \bar{X}_2)}{\sqrt{(s_1^2 + s_2^2)/n}}$	Specimen dimensions, mm cross-section / length
				σ	σ_{mrg}	$\bar{X}$	S	v, %		
Pine (USSR)	Compression	10, 9 (10, 22 – 11, 71)	18	47.6	–	2.27	0.22	9.9	7.5 > 3	20×20 / 240 (Table 1, 2 [8])
		30	18	21.0	–					
	Bending	9, 1 (8, 71 – 9, 41)	18	–	101.8	1.81	0.13	7.1		
		30	17	–	56.2					
Coniferous and deciduous trees (USSR)	Compression	15	33	45.9	–	1.82	0.20	10.8	9.8 > 3	20×20 / 240 (Table 3 [1])
		30	33	25.2	–					
	Bending	15	33	–	85.5	1.44	0.10	7.2		
		30	33	–	59.2					
Coniferous and deciduous trees (USA)	Compression	11, 8 (11, 2 – 12, 5)	77	47.1	–	2.00	0.29	14.3	7.36 > 3	50×50 / 712 (Table 21 [11])
		30	77	23.5	–					
	Bending	11, 8 (11, 2 – 12, 5)	77	–	86.5	1.70	0.19	11.3		
		30	77	–	51.5					

Note: According to [1] and [11], each mean value of σ_{br} corresponds to an individual wood species and was found by testing a large number of specimens.

Table 2

Comparison of the conditions for testing standard wood specimens in the USSR and the USA

Parameter	USSR		USA	
	Parameter values for different types of tests			
	Compression	Bending	Compression	Bending
Specimen dimensions	20×20 mm height 30 mm	20×20 mm l = 240 mm	50.8×50.8 mm height h = 203 mm	50.8×50.8 mm l = 240 mm
Number of loads per length l	–	2	–	2
Test rate	100 MPa • min^{-1}	210 MPa • min^{-1}	0.61 mm • min^{-1}	0.24 mm * min^{-1}
Test duration t'_1, min	0.4	0.356	2.46	6.5
Time to rupture t, sec lg t	0.63 −0.200	0.56 −0.252	3.87 0.588	10. 1.01

Note: Determination of test duration t'_1 in [9]: 1) compression along the grain at w = 12%, mean $E \approx$ 17,000 MPa, mean $\sigma_{\text{br}} \approx$ 420 MPa; Δh = 1.5×0.495 ≈ 1.5 mm – bearing in mind the nonlinear condition of the $\varepsilon(\sigma)$ diagram, mean l_m = 16.5 mm.

The above facts prompt the following conclusions.

1. When testing wood specimens under short-term load to assess the short-term and forecast the long-term strength of the wood, one should make sure that the values of $\lg t$ stay outside the range of paradox occurrence, which means that the loading rate must be rather slow.

2. A specimen that was subject to a constant load for a long time but did not rupture will be weaker compared to its original state owing to accumulation of irreparable submicroscopic faults [2]. If that specimen is destroyed in the test machine quickly, it should demonstrate a smaller breaking strength value. This is the technique of ‘interrupting’ the tensile strength test with trowel-shaped specimens, i.e., a test with equilibrium distribution of stress [3]. If this technique is used in a wood bending test, the decrease in σ_{br} from the accumulation of submicroscopic faults under continuous load aggregates with the decrease in σ_{br} resulting from the paradox, making it impossible to distinguish the influence of one from the other.

3. The decrease in σ_{br} resulting from the paradox that grows with the depth of cross-section of the bending element is easy to confuse with the influence of the scale factor, with which the paradox has nothing in common, because it corresponds to the difference in the resistance of specimens that are not different but identical in size and only tested at different loading rates. This is the origin of the coefficient of beam strength decrease versus the cross-section depth that was deduced on the basis of testing the beams under short-term load [12]. On the other hand, what makes sense for aeronautical frames designed to withstand high-velocity overloads does not hold true for the performance of building structures under continuous loads: here, the paradox is absent altogether, which gives no reason to use, in the wooden structure design standards, the m_6 coefficient of decrease in the designed strength of laminated beams versus their cross-section depth.

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