

ADSORPTION STRESS OF WOOD IN LONGITUDINAL DIRECTION CALCULATED ON THE BASIS OF THE MATHEMATICAL MODEL

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ABSTRACT

Hygromechanical creep of spruce wood exposed to humid air and tensiled in the longitudinal direction has been measured. The tensile stress applied did not exceed 1/3 of the tensile strength of the wood studied in wet state. The adsorption stress in the wood was determined by the indirect method proposed by Moliński and Raczkowski (1988). On the basis of the experimentally determined parameters describing the behaviour of wood creeping in the conditions of stationary and variable humidity, the adsorption stress values were calculated from the mathematical model proposed by Rybarczyk (1973). Results of the verification performed have shown that the mathematical model predictions are in qualitative and quantitative agreement with the experimental results obtained for the longitudinal direction and on exposure to humid air. A possibility of much simplified estimation of the maximum adsorption stress values with the use of the model has been also indicated.

KEY WORDS: creep, spruce wood, humidity, tensile stress, mathematical model

INTRODUCTION

Adsorption stress is the term used to describe the stress caused by restricted or fully inhibited wood swelling. Adsorption stress is measured by the mechanical stress needed to preserve unchanged size of wood subjected to moisturising, referred to as the swelling pressure (Perkitny 1951). The knowledge of the magnitude of adsorption stress generated on wood exposed to humid air is of great importance from the practical point of view, as the constructions and elements made of wood are in constant contact with air of varying humidity. As follows from the hitherto studies of the wood swelling pressure, its magnitude depends on many factors, including the method of measurement (Perkitny 1951, Ivanov 1953, Suchsland 1976, Moliński and Raczkowski 1988). On the other hand, the experimentally confirmed ability of wood to withstand the weight equal or greater than the maximum swelling forces (Mishiro 1973, Moliński and Raczkowski 1982) proves that the traditional methods of wood swelling pressure determination by direct methods do not really correspond to the actual swelling forces for different types of restriction.

From among the experimentally verified indirect methods of wood swelling pressure measurements, particularly attractive seems the one proposed by Moliński and Raczkowski (1988, 1997). In this method the adsorption stress is estimated from the hygromechanical wood strain dependence on mechanical loading. The method, based on linear relation between the hygromechanical strain on mechanical stress (Moliński and Raczkowski 1988, Wu and Minolta 1996) permits indirect determination of the stress needed for uniaxial inhibition of hygroscopic strains. Irrespective of the method applied, measurements of wood adsorption stress are much time-consuming, especially when adsorption takes place in gas environment or when the measurements are performed in the longitudinal direction. Some authors indicate a possibility of replacement of the adsorption stress measurements by calculation of its value on the basis of the known other physical or mechanical wood characteristics from simple mathematical formulae (Raczkowski 1961, Kanno 1977, Krauss 1987). However, the formulae can be applied either to a certain anatomical direction or in a certain wetting environment or to certain wood species.

Adsorption stress in wood, being a rheological property (Keylwerth 1962, Mishiro 1976) can also be determined on the basis of the quantitative description of the phenomenon by certain mathematical models. For the first time, a mathematical model has been successfully applied to a general description of mechano-sorptive behaviour of wood by Rybarczyk (1973) and Ranta-Maunus (1975), who used constitutive equations describing wood creep in the conditions of non-stationary humidity. Many later models proposed by other authors (Salin 1992, Muszyński 1997) can be eventually reduced to the equation proposed by Rybarczyk. His model describes the interrelations between the stress and strain of wood changing the moisture content in the conditions of uniaxial normal stress and strains in the same direction. The model is based on a simple formula assuming that the total strain can be expressed in terms of three components: mechanical strain due to stress only, hygroscopic strain caused only by changes in the moisture content and hygromechanical strain being a result of a combined effect of mechanical stress and moisture content changes. The theory was verified for solid wood in the transversal direction by results obtained by various authors (Rybarczyk 1973, Rybarczyk and Ganowicz 1974, Lipińska and Rybarczyk 1986).

At that time no experimental data necessary for verification of the model for the longitudinal direction were available as well as there were no reliable data on adsorption stress of the wood in this direction. The relevant results published 15 years after the model was proposed (Krauss 1988) confirmed the earlier presumptions (Stefaniak 1962, Perkitny and Kokociński 1968) that the sorptive stress in the longitudinal direction is much greater than in the transversal one. A recent study of the wood creep in the longitudinal direction on exposure to humid air (Krauss 2004a) permitted a determination of the adsorption stress values close to the real ones for this direction.

In view of the new results a question arises whether the above-mentioned mathematical model is valid in the experimental conditions (the longitudinal direction, humid air as the moistening medium) different from those in which it has been verified. As a consequence of proposing a new way of adsorptive stress measurements it seems interesting to compare the thus obtained experimental results with the theoretical predictions. The more so that for practical reasons the possibility of replacing the tedious measurements with calculations seems very attractive. Direct aim of the study was to measure the creep of tensile wood in the longitudinal direction in the stationary and non-stationary humidity and calculation of adsorption stress according to the method of Moliński and Raczkowski (1988) and assuming the model proposed by Rybarczyk (1973).

MATERIAL AND METHODS

The material on which the test was performed was spruce wood (*Picea abies* Karst.) in the form of thin wood specimens earlier successfully used in the experiments of this type (Perkitny and Jabłoński 1972, Hunt 1986, Navi et al. 1996, Krauss 2004a). The samples were in the shape of double oars of the longitudinal size of 100 mm, the radial size of 6 mm and tangential size of 2 mm. The longitudinal length of the middle narrow fragment (base of measurement) was 66 mm (Fig. 1). The samples were made of the bolt from the central log of 63 mm in thickness, seasoned in laboratory conditions. The mean moisture content of the log was 8%. From the circumferential zone of the bolt, some slabs of the cross-section of 20(T) x 15(R) mm were cut out and subjected to curving and milling in order to give them the desired shape of oars. The samples selected for the study were those of the grains parallel to the longitudinal axis and the same number of annual rings.

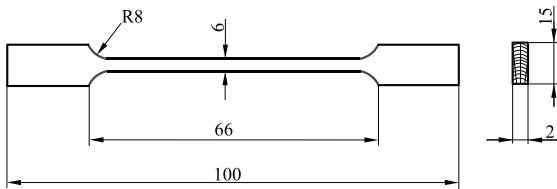


Fig. 1: Shape and size of the sample

The wood was closely ringed, of the mean width of the annual ring of 2.5 mm and the late wood fraction of 17%. The density of the wood in the oven dry state was in the range 415 ± 15 kg/m³. The hygromechanical strain of wood samples in the longitudinal direction was measured according to the method proposed by Moliński and Raczkowski (1988) and using the apparatus they designed and described (Fig. 2).

Two series of measurements were performed in the stationary and non-stationary moisture conditions. Measurements of wood creep in varied humidity were made on moisturising the samples from the oven dry state exposed to air of relative humidity of about 98% and at 294 ± 1 K. The wood samples were subjected to tensile stress of 0.12, 0.24 and 0.30 of the tensile strength in the longitudinal direction at moisture content of $13 \pm 1\%$. The absolute values of the stress acting on the samples were 10, 20 and 25 MPa. The measurements were 5 times repeated. The experiment took 6 hours. Besides measurements of hygromechanical strains, on twin samples the hygroscopic strains were observed and changes in the samples moisture content were recorded. The absolute strain measured was always referred to the preliminary measuring base of the sample.

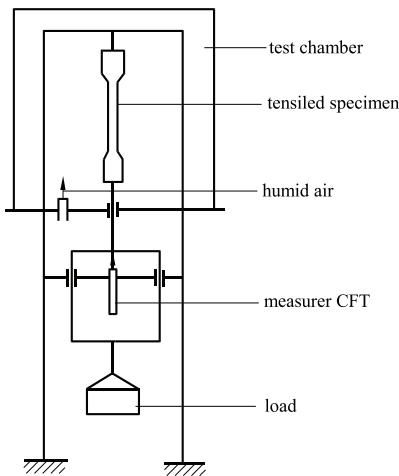


Fig.2. A scheme of the device for measurements of hygromechanical strain of wood samples

The adsorption stress in the longitudinal direction was calculated assuming the mathematical model proposed by Rybarczyk (1973). In the experimental conditions used the equation:

$$\varepsilon = \varepsilon_h + \varepsilon_m + \varepsilon_{hm} \quad (1)$$

where:

ε – total strain,

ε_h – moisture strain,

ε_m – mechanical strain (equivalent to humidity constant viscoelastic strain),

ε_{hm} – hygromechanical strain (equivalent to mechanosorptive effect);

had the solution in the following form:

$$\sigma_c^*(w) = -k/p(1-e^{-pE'w}) \quad (2)$$

where:

$\sigma_c^*(w)$ – the calculated stress needed for preserving the unchanged size of a given wood sample subject to moisturising, being a measure of adsorption stress,

w – moisture content measured as a difference between the actual and the initial moisture content,

k – coefficient of moisture strain,

p – coefficient of coupling,

E' – modulus of elasticity of long-time loaded moist wood.

RESULTS AND DISCUSSION

The results of the measured hygromechanical creep of spruce wood samples exposed to humid air (starting from the oven dry state) and tensiled in the longitudinal direction are presented in Tab. 1 as the minimum, mean and maximum values. The analogous results of the creep of spruce wood samples in the conditions of stationary moisture are given in Tab. 2. Because of a small scatter of the values measured in these conditions Tab. 2 gives the mean values only.

Tab. 1: Total strain of spruce wood samples under tensile stress applied in the longitudinal direction and subjected to moistening

Time, t (h)	Strain, ϵ (%)			
	Mechanical stress, σ (MPa)			
	0	10	20	25
0	0	0.140..0.158..0.185	0.280..0.319..0.350	0.380..0.411..0.445
1	0.103..0.120..0.133	0.285..0.332..0.385	0.450..0.495..0.528	0.565..0.605..0.628
2	0.202..0.219..0.235	0.403..0.445..0.475	0.570..0.625..0.651	0.685..0.740..0.771
3	0.241..0.275..0.301	0.475..0.509..0.542	0.680..0.710..0.732	0.774..0.829..0.862
4	0.270..0.305..0.325	0.502..0.548..0.595	0.730..0.755..0.778	0.835..0.880..0.918
5	0.282..0.315..0.338	0.530..0.572..0.612	0.763..0.785..0.810	0.878..0.921..0.956
6	0.291..0.325..0.351	0.535..0.581..0.625	0.782..0.805..0.842	0.895..0.942..0.985

Tab. 2: Mechanical strain of spruce wood samples subjected to tensile stress in the longitudinal direction in the stationary humid conditions

Time, t (h)	Strain, ϵ_m (%)								
	Mechanical stress, σ (MPa)								
	10			20			25		
	6.5	9.8	11.7	6.5	9.8	11.7	6.5	9.8	11.7
0	0.160	0.163	0.167	0.308	0.320	0.325	0.397	0.413	0.417
1	0.172	0.172	0.175	0.333	0.345	0.350	0.420	0.435	0.450
2	0.180	0.182	0.185	0.344	0.360	0.368	0.430	0.452	0.465
3	0.184	0.188	0.190	0.348	0.370	0.378	0.437	0.468	0.474
4	0.187	0.193	0.195	0.351	0.376	0.385	0.443	0.475	0.486
5	0.190	0.197	0.200	0.354	0.379	0.390	0.446	0.480	0.491
6	0.193	0.201	0.203	0.356	0.381	0.394	0.448	0.485	0.496

The effect of mechanical stress (σ) on the total strain (ϵ) during the wood creep in conditions of variable humidity, is illustrated (mean values of total strain) in Fig. 3. The isochronous course of creep presented in Fig. 3 are linear, which permits a determination of adsorption stress by the indirect method proposed by Moliński and Raczkowski (1988). On the basis of the Tab. 1 data, the regression equations were found, describing the total strain (ϵ) as a function of the tensile stress acting on the sample (σ), for the minimum, mean and maximum values of the strains recorded. The correlation coefficients of these relations range from 0.850 to 0.999. The

constants a and b in the equations type $\varepsilon = a\sigma + b$ are given in Tab. 3, also as the minimum, mean and maximum values. The same table also gives the stress (σ^*) at which the wood samples studied would not swell despite moistening, obtained by extrapolation from the regression equations. As follows from the dependencies shown in Fig. 3, the stress needed for total uniaxial inhibition of hygroscopic strain is negative so the stress is compressive. The compressive stress is a measure of the swelling pressure (Moliński and Raczkowski 1988, Moliński 2000) whose values change continuously on moisturising (Fig. 3b). The course of adsorption stress measured in the above way is qualitatively consistent with that of the adsorption stress determined by the classical direct method on inhibition of the swelling of wood moisturised in humid air (Keylwerth 1962, Krauss 2004b).

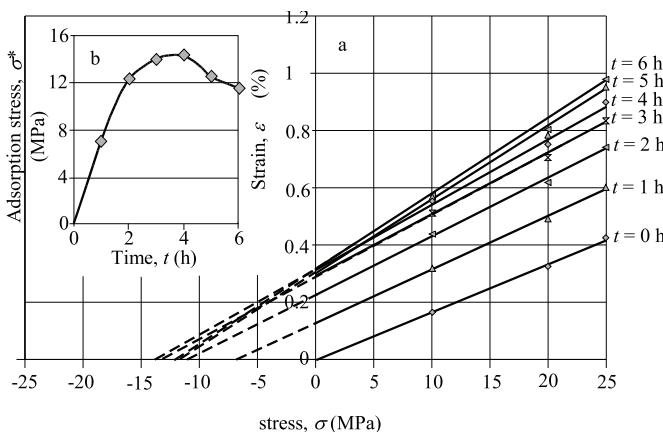


Fig.3. Total strain of spruce wood under tensile stress in the longitudinal direction and subject to moisturising versus the mechanical strain and its duration

Tab. 3: Values of the constants in the regression equation $\varepsilon = a\sigma + b$ describing total strain of spruce wood samples under tensile stress and subject to moisturising, together with the values of compressive stress corresponding to zero strain

Time, t (h)	Constant						Stress corresponding to zero strain, σ^* (MPa)		
	$a \times 10^{-4}$		$b \times 10^{-4}$						
0	149	163	176	-51	-27	26	0.3	0.2	-0.1
1	181	190	192	1015	1268	1540	-5.6	-6.7	-8.0
2	198	205	210	2047	2257	2248	-10.3	-11.0	-11.7
3	213	219	220	2493	2797	3072	-11.7	-12.8	-14.0
4	227	227	230	2725	3099	3374	-12.0	-13.7	-14.7
5	238	238	241	2858	3204	3481	-12.0	-13.5	-14.5
6	244	244	249	2921	3284	3587	-12.0	-13.5	-14.4

The adsorption stress values (σ_c^*) calculated from the assumed mathematical model are given in Tab. 4. The same table also presents the moisture content (w) and moisture strains (ϵ_h) as the mean values, and the values of the coefficients k and p needed for adsorption stress calculations (for the first and subsequent hours of the experiment) calculated on the basis of the experimental data. The coefficient of moisture strain k was calculated as a quotient of the moisture strain (ϵ_h) and sample moisture content (w). The hygromechanical coupling coefficient p was calculated as a quotient of the strain induced by the hygromechanical coupling (ϵ_{hm}) and the product of the mechanical stress (σ) and the moisture content of the sample (w). The elasticity modulus E' of long-time loaded moist wood, was calculated as the quotient of the mechanical stress (σ) to mechanical strain (ϵ_m) of wood creeping in the conditions of stationary humidity.

Tab. 4: Values of the parameters in the equation $\sigma_c^* = k/p(1 - e - pEw)$ describing adsorption stress of spruce wood samples in the longitudinal direction together with the calculated values of the stress

Time, t (h)	Moisture content, w (%)	Moisture strain, ϵ_h (%)	Coefficient of moisture strain, $k \times 10^{-2}$	Coefficient of hygro- mechanical coupling, $p \times 10^{-4}$ (MPa)			Modulus of elasticity; E' (MPa)	Calculated adsorption stress, σ_c^* (MPa)		
				min	mean	max		min	mean	max
1	5.5	0.120	2.2	4.1	5.5	7.6	6000	6.4	6.6	6.8
2	8.8	0.219	2.5	2.8	3.8	5.1	5650	11.0	11.4	11.6
3	10.5	0.275	2.6	3.1	3.5	4.3	5350	13.0	13.4	13.5
4	11.8	0.305	2.6	2.7	3.3	4.2	5150	13.9	14.3	14.5
5	12.8	0.315	2.5	2.6	3.1	4.1	5000	13.9	14.3	14.7
6	13.4	0.325	2.4	2.5	2.9	3.7	4850	13.8	14.2	14.4

The value of the strain caused by hygromechanical coupling (ϵ_{hm}) needed for the calculation of p was calculated for the time t_i as a difference between the total strain (ϵ) and a sum of the moisture strain (ϵ_h) and mechanical strain (ϵ_m) of the creeping wood of a constant moisture content corresponding to that of the wood creeping in conditions of non-stationary humidity after the exposure to humid air for the time t_i . At the time intervals at which the measurements were performed, i.e. after 1,2, ..., 6 hours, the moisture content of wood creeping in the conditions of no-stationary humidity took values by up to 1.7% of relative moisture content different from those of the wood creeping in the stationary humidity conditions. That is why the calculations of the hygromechanical strains (ϵ_{hm}) were made using the mechanical strain values (ϵ_m) taken from extrapolation of experimental data. To do this, the regression equations describing the relation between the mechanical strains (ϵ_m) and moisture content (w) were derived. The relations were linear and characterised by the correlation coefficient values in the range from 0.978 to 0.999. Therefore, for the purpose of extrapolation, a linear relation between mechanical strains and moisture content was assumed in the range of the moisture content considered.

The procedure of hygromechanical strain calculation (ϵ_{hm}) is illustrated in Fig. 4. This strain was defined as the difference between the total strain (ϵ) and the sum of the hygroscopic strain (ϵ_h) and mechanical strain (ϵ_m). Fig. 4 presents only the experimental values of the hygromechanical

creep of wood in the conditions of stationary and non-stationary humidity subjected to mechanical stress of 20 MPa and the moisture strains of wood on moisturising.

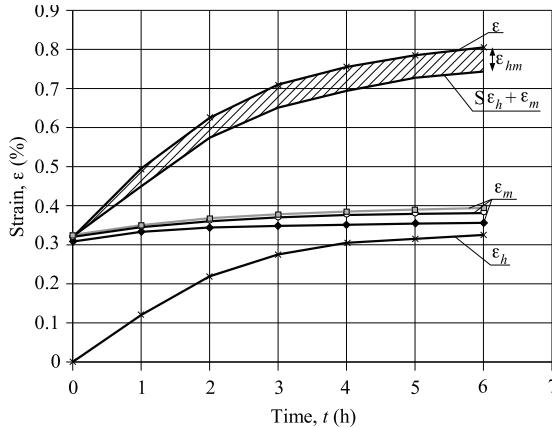


Fig.4. Moisture strain, mechanical strain, hygromechanical strain and total strain of spruce wood under tensile stress in the longitudinal direction, versus the time of moisturising.

As the content of free water has no effect on the adsorption stress and for a maximum stress to occur the moisture content of 10 – 15% (according to Keylwerth 1962) is sufficient, it was assumed that in the experimental conditions used the wood studied could reach the maximum adsorption stress. Analysis of the data given in Tabs. 3 and 4 has shown that the maxima of the adsorption stress both calculated and experimentally determined appear in the 4th hour of the process of moisturising at the moisture content of 11.8%, and their values reach 14.3 and 13.7 MPa, respectively, which is not significantly different.

As follows from Tab. 4, the values of the coefficient of moisture strain k practically do not depend on the range of the moisture changes, which indicates a linear relation between the moisture strain and moisture content of wood, which is fully consistent with the assumption of the mathematical model. The Tab. 4 data also show that with increasing range of moisture content changes the coefficient p decreases. This finding is consistent with the changes in this coefficient during wood creep in the transversal direction under tensile stress and on moisturising. The absolute values of p for the longitudinal direction are by two orders of magnitude lower than for the transversal direction (Lipińska and Rybarczyk 1986). The scatter of the calculated values of the adsorption stress is small and the values fit in the range $\pm 3\%$ relative to the mean value, thus, the curve presented in Fig. 5 has been drawn for the mean values of σ_c^* .

Fig. 5 presents the experimental data and the theoretical curve. The course of the curve and the scatter of the experimental data imply a good agreement between the calculated and measured results. The mathematical model applied, earlier verified only in the experiments with wood samples wetted in water, has been shown to well describe the wood behaviour on moisturising in humid air. The model also permits determination of the kinetics of adsorption stress. In the conditions of wood wetting in water the most important in eq. (2) is the first

term k/p . The second term e^{-pEw} takes values close to zero (Rybarczyk and Ganowicz 1974) because of high moisture content of wood on soaking in water. In description of adsorption stress changes as a function of moisture content of wood moisturised in humid air the second term of this equation becomes significant.

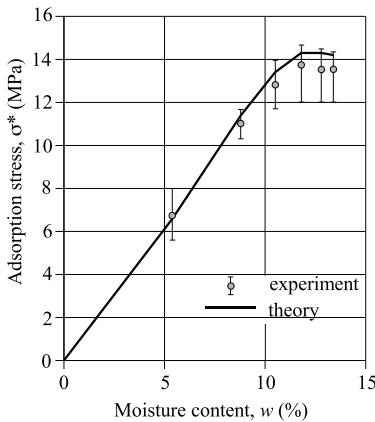


Fig.5. Adsorption stress of spruce wood determined in experiment and calculated, in the longitudinal direction, versus moisture content

The application of the mathematical model for calculations of the adsorption stress requires fewer measurements for determination of the parameters needed than the method of Moliński and Raczkowski (1988) demanding a series of wood creep measurements on different mechanical loading. Moreover, on the basis of the mathematical model the maximum adsorption stress can be calculated in a simplified way, using results of single experiments allowing determination of the hygromechanical coupling coefficient p and the wood elasticity modulus E' . As the content of free water has no effect on the adsorption stress and its maximum can be reached at a moisture content of about 12% (Keylwerth 1962), it is sufficient to determine the above parameters p and E' for a single level of moisture content to get approximate values of the maximum adsorption stress. As follows from Tab. 4, the mean value of w in the time interval between the 3rd and 6th hour of exposure to humid air, was 12.1%. The value of k was practically constant and its mean was 2.5×10^{-2} . A decrease in the coupling coefficient p and in the elasticity modulus E' was relatively small and their mean values were 3.2×10^{-4} 1/MPa and 5090 MPa. The value of the adsorption stress calculated for the mean values of the above parameters was 14.1 MPa, which was only by 0.2 MPa lower than the maximum calculated value and by 0.4 MPa higher than the maximum adsorption stress determined experimentally.

CONCLUSIONS

The above-discussed results of our experiments and calculations permit drawing the following conclusions.

- 1.The mathematical model proposed by Rybarczyk (1973) well describes the hygromechanical properties of wood exposed to humid air, measured in the longitudinal direction.
- 2.The calculated adsorption stress values fit in the range of the scatter of the experimental values determined by the indirect method of Moliński and Raczkowski (1988).
- 3.Application of the model permits a much easier estimation of the maximum adsorption stress than the use of the Moliński and Raczkowski method (1988).

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