HYGRO-MECHANICAL BEHAVIOR OF RED SPRUCE IN TENSION PARALLEL TO THE GRAIN

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ABSTRACT

The principal objective of the project was to provide a reliable testing protocol for determination of the material-level (e.g. local and decoupled from the artifacts of the test protocol) mechano-sorptive properties of wood in the longitudinal direction that could be used for modeling of the long-term structural response of wood and wood composite elements. The method also involves determination of the hygro-mechanical characteristics of free shrinkage and swelling and short-term viscoelastic characteristics from reference tests performed on matched specimens. Tensile creep tests in the longitudinal direction at varying climate conditions were performed on small (1-mm × 25-mm × 300-mm) clear specimens of red spruce (*Picea rubra*). All tests were conducted in a temperature-controlled environment. Optical deformation measurement techniques were used. Strains were calculated by comparing successive digital images using Digital Image Correlation (DIC) principles. The mechano-sorptive component of total strains measured on the loaded specimens was separated by: 1) subtracting free shrinkage/swelling measured on matched reference specimens; and 2) subtraction of the magnitude of viscoelastic creep measured separately on matched specimens at constant MC (in 'dry' and 'wet' conditions). The results confirmed earlier findings reported in the literature by other researchers that the effect of cumulative moisture content change on mechano-sorptive compliance is not linear. However, no fundamentally different governing mechanisms during the first and consecutive moisture cycles were observed. The effects of applied stress level and initial moisture content on the mechano-sorptive response of wood in tension were found insignificant at the 95% confidence level. The experimentally determined mechano-sorptive compliances were expressed in terms of generalized rheological model equations with cumulative moisture content change (rather than time) as the independent variable. Based on these findings, a minimal testing protocol was proposed for routine determination of hygro-mechanical characteristics for other structurally important species.

Keywords: Solid wood, tension, creep, mechano-sorption, experimental methodology.

INTRODUCTION

One of the most important aspects of mechanical performance and durability of wood and wood composites in structures is their response to varying climate conditions over their service life. Mechanical response of wood to immediate and sustained loading is affected by the presence of moisture and moisture changes on many levels. This behavior is not unique to solid wood and is common to many wood-based composites, paper, some hygroscopic polymers, and

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concrete (Bazant 1985; Bodig and Jayne 1993; Bazant and Yunping 1994; Muszyński et al. 2002). These phenomena, collectively referred to as hygro-mechanical behavior, include free shrinkage and swelling, effect of moisture on elastic and viscoelastic characteristics as well as the mechano-sorptive effect. When wood is subjected simultaneously to stress and moisture content changes below the fiber saturation point, the mechano-sorptive effect may be observed as an additional deformation that cannot be attributed to simple superposition of elastic deformation, free shrinkage or swelling, or creep in steady climate conditions. The mechano-sorptive effect is manifested by increased deformation in beams subjected to sustained loads and exposed to variation of service environment, which induces significant moisture changes. It also makes possible the relaxation of drying stresses during the conditioning phase of a typical kiln schedule. Modeling of the mechano-sorptive effect is therefore necessary to realistically describe the behavior of those elements while in service.

The mechano-sorptive phenomenon was first reported in the early 1950s (Perkitny 1951), and was later described as the effect of MC changes on creep behavior of wooden beams (Armstrong and Kingston 1960; Schniewind 1968). In the 1970s, it was recognized as a separate phenomenon (Rybarczyk 1973; Ranta-Maunus 1975; Grossman 1976). Many researchers proposed that the mechano-sorptive effect be quantified in terms of a compliance function, by analogy to formulations used in viscoelasticity (e.g. Rybarczyk 1973; Ranta-Maunus 1975). State-of-the-art knowledge on the mechano-sorptive effect in structural applications was summarized by Morlier (1994). Almost no literature is available on the correlation of the mechano-sorptive behavior to other material properties. Weak to insignificant correlations between magnitude of the mechano-sorptive deformation and other material characteristics (annual ring width, elastic modulus, swelling coefficient) measured on wood of a single species in bending were reported by Bengtsson (2001b). No significant effects of knots or grain angle in the specimens when compared to clear wood samples were found in the study. Although numerous theoretical explanations, mathematical models, and qualitative descriptions had been proposed, the basic mechanism of mechano-sorption has remained unclear.

Accurate prediction of the long-term mechanical performance of solid wood and wood composites, as well as the development of design code provisions that account for long-term deformations, require realistic modeling and reliable experimental data on mechano-sorptive effects covering the most commonly used commercial wood species. However, despite the fact that the mechano-sorptive phenomenon has been subject to research for more than half a century, no uniform testing protocol has been proposed or accepted, and no meaningful database of the mechano-sorptive properties of commonly used timber species is available. In fact, attempts to measure the mechano-sorptive effect in wood vary greatly in experimental design, and assumptions applied make it impossible to meaningfully compare experimental data or use it as a guide for development of structural design codes. It is apparent that the experimental determination of basic mechano-sorptive parameters on the material level, understood as a local property decoupled from artifacts of moisture and stress gradients in the testing protocol, and particularly decoupled from time-dependent moisture diffusion, remains a serious challenge (Morlier 1994). A simplified, standard test method to measure the mechano-sorptive effect is suggested in this paper.

Strain components in wood may generally be assumed as independent from each other, and hence when the effect of temperature and thermal expansion is neglected, strain in wood under axial load is often expressed as a linear superposition:

$$\varepsilon\,(\sigma,t,MC,\Delta MC,\ldots) = \varepsilon_{ve} + \varepsilon_{\alpha} + \varepsilon_{MS}, \quad (1)$$

where ε_{ve} is the viscoelastic deformation (including immediate and delayed response); ε_{α} is *free* shrinkage or swelling; and ε_{MS} is the mechano-sorptive deformation, which is defined as the *additional* deformation that cannot be explained as a simple superposition of the former two. This simple conceptual distinction is based on three different combinations of trigger mechanisms for each of the strain component. In reality, however, the mechano-sorptive deformation as a second-order phenomenon is always accompanied by viscoelastic deformations and free swelling or shrinkage, and hence cannot be measured directly or easily isolated. It should be stressed, however, that once the mechano-sorptive effect is defined as additional deformation that cannot be expressed as simple superposition of viscoelastic and *free* hygro-expansion, further speculation on the effect of stress on *free* hygro-expansion (as it is occasionally reported), appears to be a conceptual error resulting from secondary "redistribution" of the mechano-sorptive component.

An additional complication comes from the fact that hygro-mechanical effects are always coupled with a time dependent-moisture diffusion. Although a reverse effect, i.e. effect of stress on sorption isotherms of wood is also reported, it is relatively small and thus is neglected here. In varying climates, the effect of dynamic and nonuniform distribution of moisture on mechanical characteristics of wood (Gerhards 1982) results in internal non-homogeneities that depend strongly on the specimen size, as well as duration and nature of the climate changes. The importance of this is that the characteristics obtained from procedures following standard flexural tests but involving varying climate, where the nonhomogeneities coincide with a nonuniform stress pattern, cannot be extrapolated to different element sizes and test conditions. As such, the flexural tests on beams undergoing moisture distribution changes generally fail to provide valid material-level mechano-sorptive parameters (Morlier 1994; Muszyński et al. 2005).

The effect of a moisture gradient across the section is significantly reduced in axial tests on specimens small enough to allow fast exchange of moisture with the environment. Various methods based on axial tests have been proposed (Hisada 1986; Muszyński and Olejniczak 1996; Wu and Milota 1996; Hunt 1997; Bengtsson 2001a). The general methodological aspects of the quantitative determination of the hygro-mechanical properties of wood are discussed in (Muszyński et al. 2005).

There is common agreement that the magnitude of mechano-sorptive deformation depends on the applied stress level and increases with the cumulative MC change (ν) or a sum of absolute values of monotonic moisture content changes below the FSP (Rybarczyk 1973; Ranta-Maunus 1975; Choi and Shah 1997; Hunt 1997):

$$\varepsilon_{MS} = f(\sigma, \nu) \tag{2}$$

where:

$$\nu = \int_t |\dot{w}| dt \cong \sum_i |\Delta w_i|, \tag{3}$$

$\dot{w}$ is the MC change rate and Δw_i are monotonic MC changes. Therefore, model equations for the mechano-sorptive deformation are most conveniently fitted to the experimental data in the cumulative MC change (ν) domain rather than a time domain, so that clearly defined quantitative material characteristics may be determined. The remarkable convenience of this formulation is often underestimated.

The principal objective of the project was to provide a reliable testing protocol for routine determination of the material-level mechano-sorptive properties of wood (in the longitudinal direction) that could be used for modeling of the long-term structural response of wood and wood composite elements. By material-level characteristics, we understand local properties of presumably a homogenous volume of material, decoupled from the artifacts of the testing method or conditions. Such defined material-level characteristics contrast with structural level characteristics, where the examined properties are attributed to a specimen or element of particular geometry as a whole, and are significantly affected by loading configuration, testing and moisture gradient conditions, and other difficult to eliminate artifacts. The specific goals were: 1) Examine the existence and significance of the secondary features of the mechano-sorptive effect, including: a) different response to the first and consecutive climate cycles, and b) influence of stress level; 2) Based on the findings, develop a simple but reliable experimental method for determination of basic hygro-mechanical properties of wood: free shrinkage and swelling coefficients, effect of MC on short-term viscoelastic characteristics, and mechano-sorptive characteristics. The latter were expressed as parameters of generalized rheological models proposed by Rybarczyk (1973).

MATERIAL AND TEST METHOD

Tests were performed on small clear specimens (L × W × t = 300 mm × 25 mm × 1 mm) of red spruce (*Picea rubra*) fabricated from mature sapwood cut from logs. The width of the specimens was determined so that no less than 10 annual rings were fully included. The method used in the study followed the general methodology first developed by Muszyński and Olejniczak (1996) for determination of mechano-sorptive compliance of wood in the transverse direction and then improved and applied by Muszyński et al. (2002) to thin resin films. The methodological aspects of the quantitative determination of the hygro-mechanical properties of wood are discussed in greater detail in (Muszyński et al. 2005).

Three groups of tests on carefully matched clear wood specimens were carried out to enable separation of the principal components of axial strains. In the first test group, the total deformation was measured on specimens subjected to load and cycling changes of relative humidity (RH) in a small controlled climate chamber. Three load levels (30%, 50%, and 70% of tensile strength in green condition) were used. The second test group consisted of simultaneous measurement of moisture content (MC) changes and the free shrinkage/swelling deformation monitored on unloaded specimens subjected to the same climate changes. Finally, the magnitude of the viscoelastic component of deformation over the test duration was evaluated by reference creep tests at constant MC conditions (at 30% and 95% RH) on matched specimens. Only two reference moisture levels were selected, because as shown in the following sections, the creep component is usually only a small fraction of the total deformation in relatively short-time tests. The outline of the experimental plan is summarized in Table 1. Eight specimens were tested in each experimental condition (in two sets of three loaded and a reference specimen).

Test setup

Specimens were loaded in tension in a loading frame with a system of levers and wedge-grips to provide adequate clamping when specimens shrink during drying cycles. Four specimens (three loaded and one reference) were tested at a time. All tests were conducted in temperature-controlled environment at 21° C, ±2° C. A computer-controlled climate chamber was developed to maintain the relative humidity at specified levels (± 2% RH). The climate controlling system consisted of an ultrasonic humidifier to provide cold mist, a dry air source, air mixing chamber, an air redirecting valve, and a temperature/RH sensor connected to a data acquisition system. A balance (± 0.001 g) was used to record weight changes on reference specimens in order to calculate moisture content (MC) values as RH changes occurred. A schematic of the test setup is shown in Fig. 1.

Digital image correlation (DIC) technique

All deformations were determined using a noncontact digital image correlation (DIC) tech-

TABLE 1. *Outline of the experimental plan.*

Test	Load levels (% UTS*)	Number of specimens	Strain component ε_{ve}	ε_{α}	ε_{MS}
Creep in cyclic	30%	6			
RH (start at wet	50%	6	X	X	X
condition)	70%	6			
Creep in cyclic	30%	6			
RH (start at dry	50%	6	X	X	X
condition)	70%	6			
Creep in constant	30%	6			
'wet' condition	50%	6	X		
	70%	6			
Creep in constant	30%	6			
'dry' condition	50%	6	X		
	70%	6			
Free shrinkage	Unloaded			X	
and swelling	references	12			

* UTS = Ultimate Tensile Stress @ green condition.

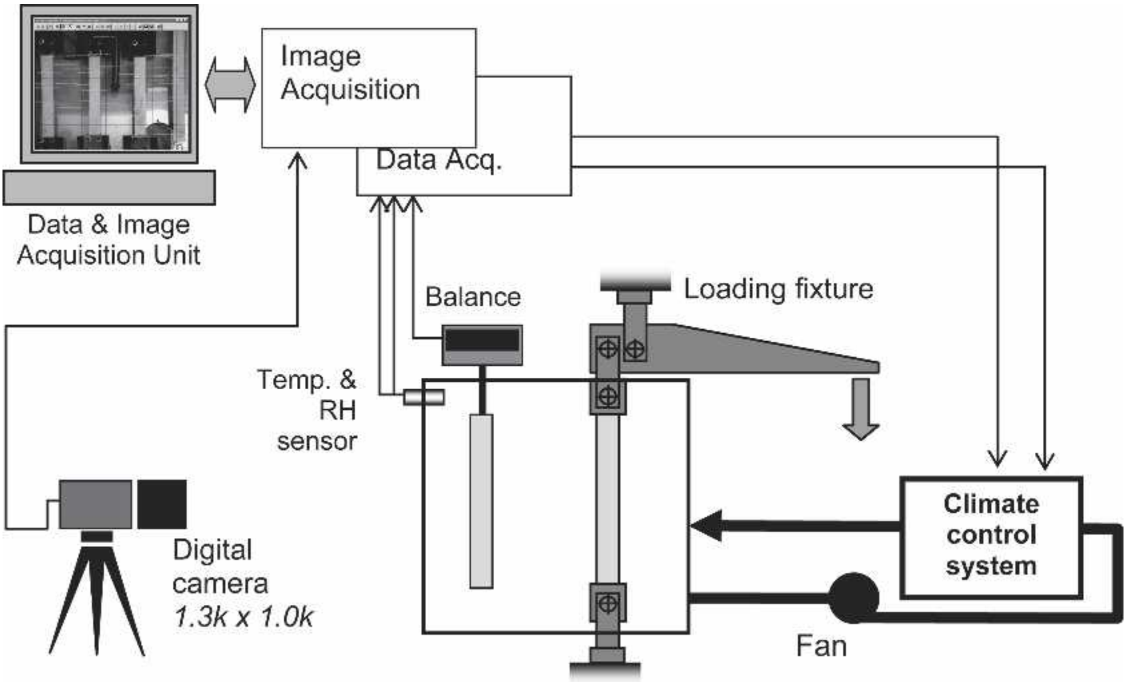

FIG. 1. Experimental setup.

nique. This method has been developed and used to measure deformation and strains of materials under various loading regimes with sub-pixel accuracy since the late 1980s (Ranson et al. 1987; Bruck et al. 1989; Vendroux and Knauss 1998). It has been already successfully applied to determine strains in specimens of solid wood, individual wood fibers and paper (Sutton and Chao 1988; Mott et al. 1996; Choi and Shah 1997), as well as Fiber Reinforced Plastics (FRP) (Muszyński et al. 2000), concrete (Choi et al. 1991), and resin films (Muszyński et al. 2002).

One of the advantages of application of the noncontact optical measurement of strains versus strain gages or mechanical extensometers was significant simplification of specimen handling procedure and reduction of the specimen setup time. The method allows the determination of displacements of selected points on the surface of the deformed specimen by comparing successive images acquired during tests and cross-correlating the grayscale intensity patterns of reference areas composed of adjacent points. Transverse and shear strain values for deformation of specimen surfaces could be obtained from analysis based on a triangular network of points (Muszyński et al. 2002). A detailed description of the method may be found in (Ranson et al. 1987; Bruck et al. 1989; Choi et al. 1991; Choi and Shah 1997).

During the tests, the images of specimens were acquired by means of two high-resolution digital cameras (1296 × 1024 pixels) with 50-mm lenses, controlled by a personal computer using a camera controller card. Analysis of the digital images acquired at discrete time intervals during the experiments was performed by means of Sherlock32™ software (© 1999 by Imaging Technology Inc).

Calibration procedures

A thorough test setup and method calibration were performed to ensure necessary precision of the optical measurement. The calibration procedure included: 1) Alignment of the loading frame and grips to ensure that accurate optical measurements could be performed from the side view of the specimens; 2) Calibration of the climate chamber performance and determination of the optimal cycle duration; 3) Calibration of the optical system to determine adjustments for lens distortion; 4) Calibration of the image and data acquisition system to determine practical resolution of the Digital Image Correlation (DIC); and finally, 5) Testing of the entire procedure to evaluate accuracy of the method.

Theoretical resolution of the DIC software was 0.05 of a pixel size; however, the practical resolution of DIC is limited by actual conditions (e.g. appearance of the specimen surface, quality of lenses, lighting etc.). A typical best resolution was 0.066 of a pixel size, defined as 1.645 standard deviation (or 95% confidence range) of location of static grid on an undeformed specimen measured on 30 images. The accuracy of strain measurement depended on chosen measurement gage (from $8.3 * 10^{-5}$ mm/mm to $2.5 * 10^{-4}$ mm/mm for gage lengths of 800 to 300 pixels, respectively).

Data treatment and analysis

The mechano-sorptive component was calculated from the total deformation determined in course of creep tests under cycling climate conditions by subtracting the free shrinkage/swelling, and the viscoelastic deformations (including the immediate component) adjusted for current MC. The data treatment process is summarized in Fig. 2

RESULTS AND DISCUSSION

The humidity cycle duration was determined in a separate series of tests on unloaded specimens. Due to small cross-section dimensions of the specimens, significant MC changes (about 10% MC) could be achieved by 60-min wetting/drying phases.

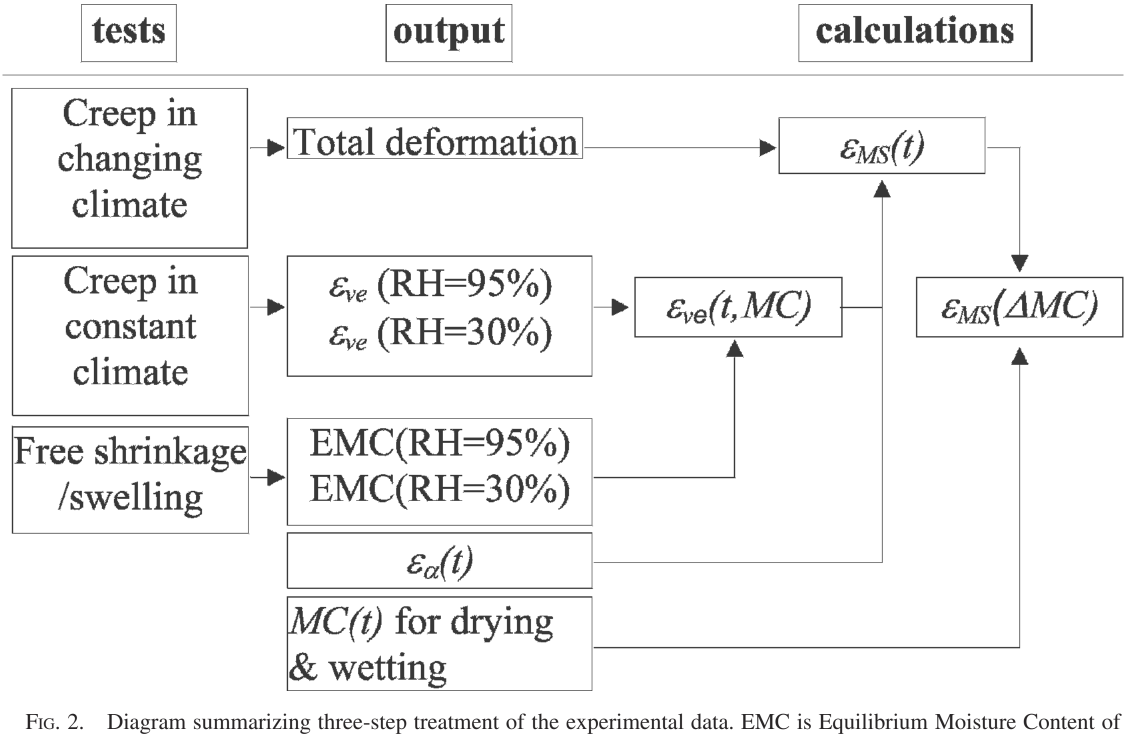

FIG. 2. Diagram summarizing three-step treatment of the experimental data. EMC is Equilibrium Moisture Content of wood at given ambient conditions (temperature and RH).

Sample results from tests in a cyclic climate are shown in Fig. 3. Theoretical curves for viscoelastic creep at wet (95% RH) and dry (30% RH) conditions obtained from the reference creep tests by fitting standard 3 parameter solid equations are also shown for comparison. Generally, creep properties of wood are believed to depend on load level and ambient MC (Bodig and Jayne 1993). In the current study, however, the magnitude of the viscoelastic deformations at constant RH conditions was found to be relatively small (about 8% of total deformation after 17 h) and its dependence on load level and MC statistically insignificant (experiment-wide alpha = 0.05) when compared to the accuracy of measurement of the compliances determined at constant dry and constant wet conditions. Given the relatively small MC change, linear dependency of the tensile elastic modulus on MC was assumed.

The mechano-sorptive deformation extracted from the same set of data is shown in Fig. 4. Maximum shrinkage/swelling (FSP to oven-dry) and shrinkage/swelling ratios per unit change of MC in the longitudinal direction, calculated for 12 unloaded reference specimens (green dimension base) are shown in Table 2. The maximum longitudinal shrinkage was 0.264%, while the maximum longitudinal swelling was 0.265%. The respective shrinkage and swelling ratios were 0.00944 and 0.00946% strain per % MC.

The magnitude of total strains (corrected for free shrinkage/swelling) after 16 h of testing in cyclic climate conditions (8 complete humidity cycles) as well as immediate, delayed, and mechano-sorptive strain components expressed as fractions of total deformation for all test conditions were relatively consistent for all conditions: 67%, 9%, and 24% respectively (Table 3).

As evident from the sample graph in Fig. 4, the mechano-sorptive deformation is a function of cumulative moisture content change and the dependence is not linear. The deformation rate decreased with the cumulative MC change, so that the largest deformation rate was coincident with the first MC cycle. For single monotonic climate changes, the response might be interpreted as almost linear (compare the linear models proposed by Rybarczyk (1973) and Ranta-Maunus (1989)). This behavior is sometimes described by a bi-linear model, where different mechano-sorptive compliances are attributed to the first and the consecutive MC cycles (Ranta-Maunus 1975). The decreasing deformation rate, however, may be much better described with a

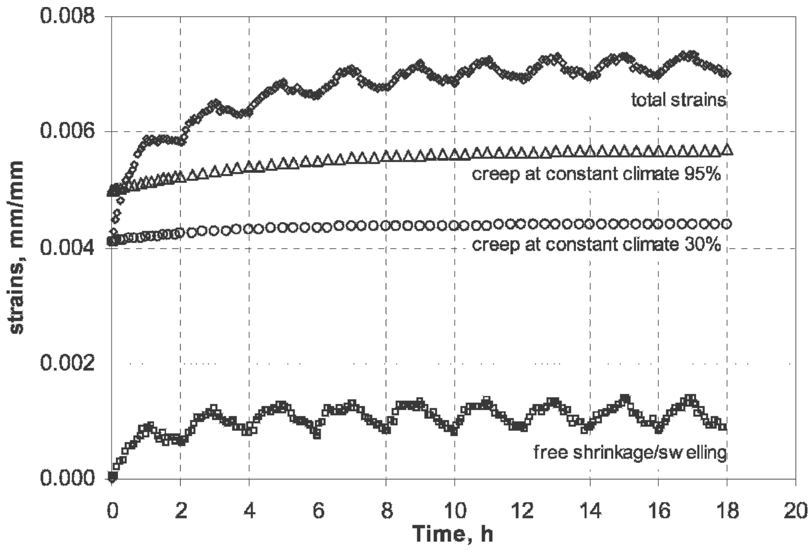

FIG. 3. Sample results from a set of tests at load level of 70% of green UTS.

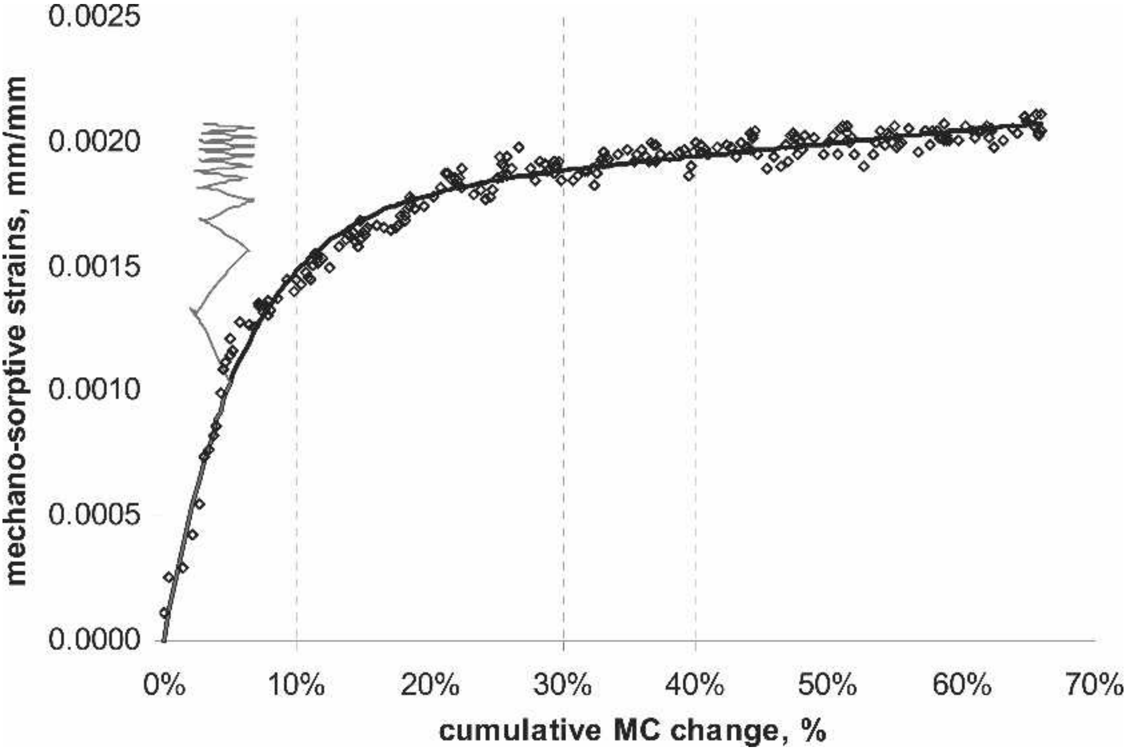

FIG. 4. An example of mechano-sorptive deformations presented in the MC domain (a) and cumulative moisture content change (ν) domain (b).

TABLE 2. *Free shrinkage/swelling in longitudinal direction measured on reference specimens.*

	Max [%]	Ratio [%/%]	C.O.V.
Shrinkage	0.264	9.44e-3	17.2%
Swelling	0.265	9.46e-3	17.2%

single continuous exponential curve as proposed by Rybarczyk (1973) and Salin (1992).

Three-parameter model equations in the cumulative MC change (ν) domain, analogous to a rheological model with one Kelvin and one dashpot element combined in a series (Eq. 4), were fit to the experimental mechano-sorptive data to obtain characteristic compliance parameters.

$$J_{MS}(\nu) = \frac{1}{E_{MS}}(1 - e^{-\nu\, m_1 E_{ms}}) + m_2 \nu \qquad (4)$$

where J_{ms} is mechano-sorptive compliance; m_1, m_2, and E_{ms} are model parameters; and ν as defined in Eq. (3). The principal advantages of projecting the mechano-sorptive deformation to a cumulative moisture content domain is that it can be perceived and analyzed as one smooth process, regardless of the process duration (stretches of steady climate conditions appear compressed to single points) and number of effective MC changes, and that the mechano-sorptive compliances can be expressed as a con-

TABLE 3. *Proportions of total strain components after 8 two-hour MC cycles (16 hours of testing).*

Load level	Initial cond.	Total str. mm/mm	Strain components as % of total: Elastic	Delayed	MS
30%	Wet	0.00329	65%	8%	28%
	Dry	0.00313	67%	9%	25%
50%	Wet	0.00462	71%	9%	20%
	Dry	0.00471	66%	9%	25%
70%	Wet	0.00682	67%	8%	25%
	Dry	0.00645	69%	8%	22%
Means at all conditions		—	67%	9%	24%

tinuous function of ν (Muszyński et al. 2005). The viscoelastic and mechano-sorptive model parameters obtained in this study are summarized in Table 4.

The statistical significance of some secondary features of the mechano-sorptive phenomenon for red spruce sapwood was examined. Statistical treatment of the results is described in detail in (Lagana 2005). The effects of the applied stress level and the initial moisture content on the mechano-sorptive response of wood in tension were found insignificant when compared with the measurement error at the 95% confidence level. The findings are summarized in Table 5. It should be stressed, however, that these conclusions are drawn from tests on clear mature sapwood of a single species.

Based on these observations, a simplified test method for routine determination of mechano-sorptive properties of wood was proposed. The tensile specimen dimensions ($L \times W \times t = 300$ mm × 25 mm × 1 mm) were found adequate for the mature sapwood of red spruce. However, it may be necessary to fabricate narrower specimens for species with narrow sapwood, or wider specimens for fast-grown species, so that no less than 10 annual increments are fully included in the specimen to ensure relative homogeneity. The principal changes when compared with the original test protocol described above are: 1) All tests may be performed on the same stress level all cycles starting with the same MC. 2) Reference creep-at-constant-climate tests at 50% RH and a single stress level are recommended. The effect of the MC level on the time-dependent deformation may be safely neglected. 3) Because the mechano-sorptive characteristics are determined from a multistage procedure, measurement errors can accumulate, resulting in relatively higher variation of the results. The sample size should be designed accordingly to minimize this effect (12 specimens per condition is suggested). The simplified test protocol is summarized in Table 6.

Table 4. *Summary of viscoelastic and mechano-sorptive model parameters for red spruce at 'dry' and 'wet' conditions.*

Initial conditions		Model parameters					
		Visco-elastic			Mechano-sorptive		
RH	EMC	E_0 GPa	E_1 GPa	η GPa*h	E_{MS} GPa	m_1 1/GPa	m_2 1/GPa
30%	7.1%	14.9	121	480	38.1	0.504	0.005
90%	17.3%	13.2					

Table 5. *Summary of the statistical analysis of the significance of stress level and initial moisture content.*

Hypothesis (95% confidence level)	Creep at constant climate	Mechano-sorptive creep
Significant stress level effect	No*	No
Significant effect of the initial MC	No*	No

* Conclusions valid for the reference 18-h creep tests.

CONCLUSIONS AND FURTHER WORK

A three-step experimental testing protocol was applied to determination of basic hygro-mechanical characteristics of clear homogenous specimens of clear mature sapwood of red spruce. The optical method had been successfully applied to measurement of deformation of small wooden specimens subjected to tensile load under changing climate conditions.

The testing protocol allowed comprehensive strain component separation and generated a set of hygro-mechanical characteristics including free shrinkage/swelling coefficients, viscoelastic and mechano-sorptive compliance curves.

The primary findings for this material are summarized as follows: 1) It was confirmed that the mechano-sorptive deformation development is dependent on cumulative moisture content change, that the dependence is not linear, and that it could be well described with a single exponential equation. 2) At 95% confidence level, no significant effect of the applied stress level on the mechano-sorptive response of wood in tension was observed over the cumulative moisture content range investigated. 3) At 95% confidence level, no significant effect of the initial moisture content on the mechano-sorptive response of wood was observed in tension.

The mechano-sorptive compliances measured during the experiments were expressed in terms of generalized rheological model equations (i.e.

TABLE 6. *Outline of the simplified test protocol.*

Tests	Load level (% UTS*)	No. of specimens	Strain components ε_{ve}	ε_{α}	ε_{MS}
Creep in cyclic RH (30% to 90%)	50%	12	x	x	x
Creep in constant condition (50% RH)	50%	12	x		
Free shrinkage/swelling (30% to 90%)	Unloaded	3		x	

* UTS = Ultimate Tensile Stress @ green condition.

functions of cumulative moisture content changes). The advantage of such an approach was that the mechano-sorptive deformation could be analyzed as one smooth process spanning multiple MC cycles, and decoupled from the elapsed experiment time. The characteristic compliance parameters were determined by curve fitting.

Based on these findings, a minimal testing protocol was proposed for routine determination of hygro-mechanical characteristics for other structurally important species.

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