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MOISTURE BEHAVIOUR OF RECENT AND NATURALLY AGED WOOD

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ABSTRACT

Furniture and other wooden objects in historic buildings are often exposed to important variations in relative humidity. Degradation effects resulting from cyclic or irreversible swelling and shrinkage of wood are well known and pose an important threat to the preservation of our cultural heritage. This paper reports differences in behaviour between recent and naturally aged wood. Sorption hysteresis measurements were carried out at room temperature. The response of wood to moisture variations, i.e. swelling and shrinkage, was tested in different steps of relative humidity simulating realistic conditions. Additionally, Young's and shear moduli were calculated from ultrasound velocity. The results demonstrate little if any difference between the two groups, indicating that conclusions drawn from the study of modern wood are also valid for historic wood in good condition. Finite element modelling of the deformation of wooden panels subjected to environmental changes demonstrates that works of art coated with a layer of reduced permeability on one side are more at risk from mechanical damage through deformation than objects without coating.

KEYWORDS: Dimensional stability, elastic moduli, finite element modeling, moisture, relative humidity.

INTRODUCTION

Fluctuations of relative humidity (RH) are a major risk factor for the conservation of historic wooden objects. Fig. 1 shows temperature and RH curves over a period of seven months inside a historic building without environmental control, the Musée d'art et d'histoire in Geneva, Switzerland. The observed seasonal fluctuations between ca. 15 and over 60 % RH, are typical for uncontrolled indoor environments in central Europe. Depending on aeration, summer peaks may even rise to 75 % RH and above. There are also important short-term fluctuations over 2-4 days depending on weather conditions, as well as day-night cycles.

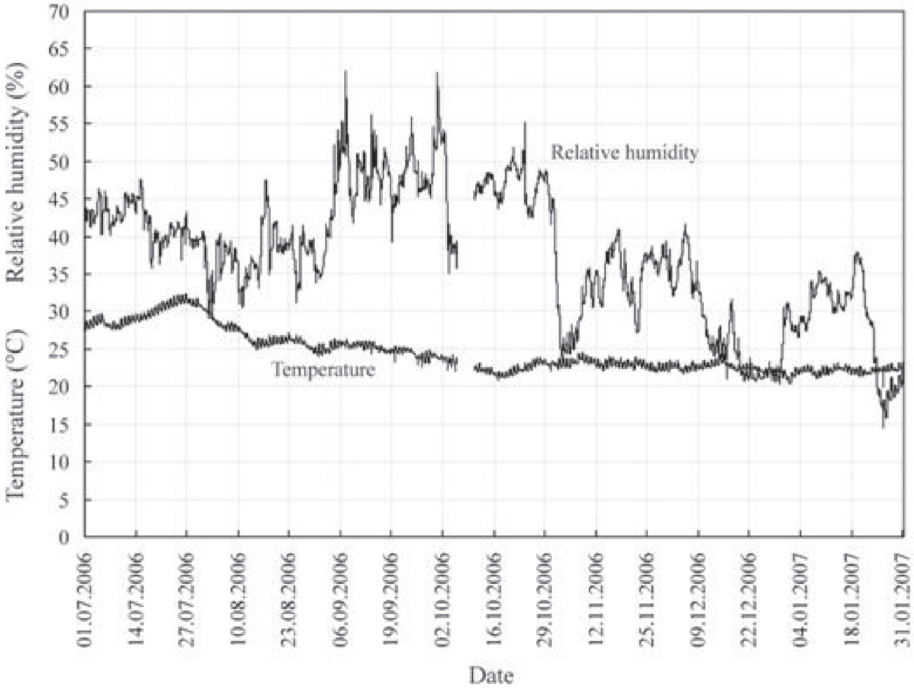

Fig. 1: Variations in temperature and RH in an uncontrolled indoor area (Egyptian gallery, Musée d'art et d'histoire, Geneva) over a period of seven months

Environmental conditions have a significant effect on the alteration of wood properties with time. Possible insect attack apart, wood does not significantly deteriorate when maintained in a stable, favourable environment (Lohmann 2003). In resonance wood stored for several decades, a 10 % increase of the modulus of elasticity and reduced variations of swelling and shrinkage coefficients were observed. Both can be explained by a complete disappearance of growth stresses (Lohmann 2003). However, excessive moisture may lead to fungal damage and decay. Also, heating of interior rooms, especially modern central heating, gives rise to deformation and cracking due to drying of the wood during the heating periods. For *Pinus sylvestris* L. stored 300 years in an uncontrolled environment, Erhardt et al. (1996) found no significant differences to new wood for a number of mechanical and physical characteristics including strength, stiffness, elasticity, and response to changes in relative humidity (RH). Minor chemical changes were detected in resin and cellulose. The results of Erhardt et al. (1996) as well as conservation experience with historic buildings and interiors demonstrate that wooden objects safely tolerate moderate fluctuations of temperature and RH.

The aim of this paper is to compare mechanical and physical properties of historic (ca. 150-500 year old) and recent hard- and softwoods as a part of a more general study to determine the extent to which such fluctuations can be tolerated in museum environments, and the limits when objects are beginning to be at risk.

MATERIAL AND METHODS

Material

The different timbers used for the experiments are listed in Tab. 1. Naturally aged and recent samples of three wood species were investigated: European oak (*Quercus robur*), Norway spruce (*Picea abies*) and silver fir (*Abies alba*). The aged samples were collected from 16th to 19th century buildings throughout Europe. The age of the wood was determined either by dendrochronology or deducted from the known history of the building from which the material was taken.

Dimensional moisture isotherm measurement

Swelling and shrinkage of wood as a response to RH fluctuations in the environment are essential characteristics, as they potentially lead to deformation and mechanical damage to wooden cultural heritage. Their values were determined perpendicular to the grain in radial and tangential directions at 20°C. Specimen dimensions were 25 or 50 mm in radial and tangential directions (Tab. 1) and 10 mm in longitudinal orientation. All specimens were initially conditioned at 65 % RH and then transferred to conditions of 80, 93, again 80, 65, 50 and 35 % RH, after which they were oven dried at 103°C and again humidified at 35 and 50 % RH. In all cases, the specimens were conditioned until equilibrium was reached. At this point, their mass and dimensions were recorded. Adsorption and desorption of wood yield different sorption isotherms. The equilibrium moisture content (EMC) is larger in desorption than in adsorption mode (hysteresis of the sorption curve). The linear swelling q in % is calculated from the dimension under wet conditions α_1 and the dimension after kiln drying α_0 as

$$q = \frac{\alpha_1 - \alpha_0}{\alpha_0}\ (\%) \tag{1}$$

Elastic moduli measurements

In order to determine Young's and shear moduli through ultrasound velocity measurements, two wave types were used: longitudinal and transversal. Longitudinal waves oscillate in the direction in which they propagate while transversal waves oscillate perpendicular to their direction of propagation. The velocity of sound is significantly influenced by the wood structure. In longitudinal direction, it is three to four times greater than perpendicular to the grain (Niemz 1993). Sound velocities were determined using a sound measuring instrument Epoch XT (Olympus). Cubes with dimensions of 10 mm were clamped between two transducers (Panametrics). In order to ensure the same pressure for all specimens, the transducers were initially placed at a distance of 8 mm using a block of acrylic resin. Ultragel II (Sonotech) was used as a coupling agent between sample and device. The longitudinal wave frequency was 2.23 MHz, the transversal frequency 1.00 MHz. The moduli were approximated by

$$G_{ij} = c_{ij}^2 \cdot \rho, \qquad E_{ii} = c_{ii}^2 \cdot \rho, \tag{2}$$

where: c_{ij} (i≠j) and c_{ii} ($m.s^{-1}$) are the sound velocities of the transversal and the longitudinal waves, respectively. The direction towards propagation of the wave is indicated by i and the direction of oscillation of the transversal wave as j. The density of the sample is termed ρ ($kg.\ m^{-3}$).

Tab. 1: Wood material used in the experiments – identification, age and sample length for sorption measurements

Identification	Wood species	Approx. age (years)	Sample length (mm)
Oak/age/1	*Quercus robur*	260	50
Oak/age/2	*Quercus robur*	470	25
Oak/rec	*Quercus robur*	recent	50
Spruce/age/1	*Picea abies*	250	50
Spruce/age/2	*Picea abies*	160	50
Spruce /age/3	*Picea abies*	320	25
Spruce/age/4	*Picea abies*	320	25
Spruce /age/5	*Picea abies*	160	25
Spruce/rec	*Picea abies*	recent	50
Fir/age/1	*Abies alba*	470	25
Fir/age/2	*Abies alba*	480	25
Fir/age/3	*Abies alba*	280	25
Fir/age/4	*Abies alba*	280	25
Fir/age/5	*Abies alba*	180	25
Fir/rec	*Abies alba*	recent	25

Simulation

Understanding the wood response to changes in relative humidity is very important for the preservation of cultural heritage. Moisture changes imply swelling and shrinkage, and in extreme cases damage in form of irreversible deformation and cracks. For this study, the moisture impact was simulated using the finite element method (Bathe 1996, Zienkiewicz and Taylor 2000). The calculation of the diffusion process within the material was based on the Fick's law of diffusion. For the material data for spruce wood and for the adhesive layers see Gereke et al. (2009). The surface impermeability of wood was taken into account by applying a surface emission coefficient h ($m.s^{-1}$). The flux vector J with the normal vector n is driven by the difference in moisture concentrations corresponding to the ambient air, and on the surface, c_a and c_s, ($kg.m^{-3}$).

$$\mathrm{nJ} = h(c_a - c_s) \tag{3}$$

Three-layered 30 mm thick cross-laminated spruce panels were modelled, with different surface emission coefficients for one of the two surfaces. This allowed simulating a coated surface on one side, with lower moisture permeability. The opposite surface was assumed to be not coated. The initial climate was assumed to be 50 % RH. In the model, the panels were then dried at 25 % RH. Moisture transport was assumed to be one dimensional through the large surfaces.

The mechanical material model used in the present study was previously validated against deformations of dried wooden sticks by Ormarsson (1999) and to moisture-induced stresses and deformations of cross-laminated timber by Gereke (2009). The three-dimensional model assumes the total strain rate $\dot{\varepsilon}$ to be the sum of the elastic strain rate $\dot{\varepsilon}_{el}$, the moisture-induced strain rate $\dot{\varepsilon}_{\omega}$ and the mechano-sorptive strain rate: $\dot{\varepsilon}_{\omega\sigma}$

$$\dot{\varepsilon} = \dot{\varepsilon}_{el} + \dot{\varepsilon}_{\omega} + \dot{\varepsilon}_{\omega\sigma} \qquad (4)$$

The dot denotes the derivative with respect to time. All material matrices and data are presented in Gereke (2009).

RESULTS AND DISCUSSION

Dimensional moisture isotherm measurements

The results for swelling and shrinkage between the oven dry state and 93 % RH are displayed in Figs. 2 (adsorption) and 3 (desorption) for the three wood species. The relation between swelling and moisture content approaches linearity for all series. For spruce wood, the mean values for the aged samples are greater than for the recent samples, whereas for the other two species they tend to be smaller or the same. However, due to the relatively large variation for the aged samples, this difference is not significant and remains within the natural spread. This coincides with earlier reports (Erhardt et al. 1996, Holz 1981, Unger et al. 2001). The isotherms for the other species are essentially the same, meaning that the responses to changes in RH of aged and recent wood can be taken as identical. Although the behaviour of the aged wood when it was new is not known, it was likely to be very similar to that of the recent specimens. Due to the larger number of specimens, the standard deviation of the aged samples is higher. However, the standard deviation between the single groups of one wood species (Tab. 1) does not significantly vary.

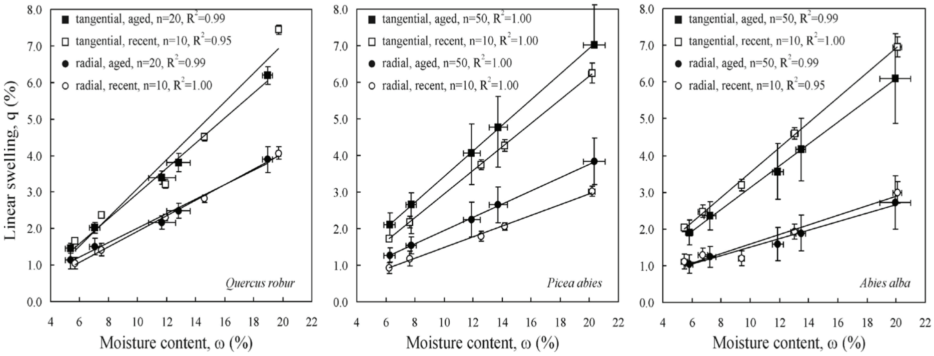

Fig. 2: Linear swelling of oak, spruce and fir in radial and tangential direction (mean and standard deviation, n=10)

A reduced variation of swelling and shrinkage coefficients, as it was reported earlier (Lohmann

2003), cannot be confirmed for the investigated species. There is no significant influence of different densities within one wood species on swelling and EMC.

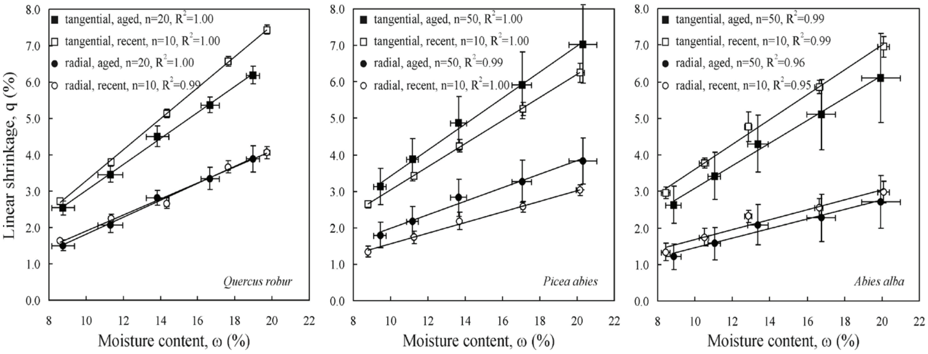

Fig. 3: Linear shrinkage of oak, spruce and fir in radial and tangential direction (mean and standard deviation, n=10)

Elastic moduli measurements

The results of the ultrasound measurements are shown in Tab. 2 for oak wood and in Tab. 3 for spruce wood. The Young´s modulus is greatest in longitudinal direction, the radial Young´s modulus being about twice the tangential. Taking into account the relatively large data spread associated with the analytical method, as well as the considerable natural variation of wood properties within the same species, no significant differences between aged and recent wood are detectable.

Tab. 2: Stiffness parameter of oak at 20°C and 65 % RH measured using ultrasonic waves (n=10)

ID		E_L (N.mm^{-2})	E_R (N.mm^{-2})	E_T (N.mm^{-2})	G_{LR} (N.mm^{-2})	G_{LT} (N.mm^{-2})	G_{RT} (N.mm^{-2})	ρ (kg.m^{-3})
Oak/rec/1	Mean	17075	4023	2528	1536	1211	536	712
	STD	2685	95	42	216	95	73	5
Oak/rec/2	Mean	19185	3868	2130	1597	943	485	669
	STD	966	55	61	121	84	16	13
Oak/age/1	Mean	12001	2958	2201	984	1125	432	607
	STD	2723	336	138	83	68	32	25

Tab. 3: Stiffness parameter of spruce at 20°C and 65 % RH measured using ultrasonic waves (n=10)

ID		E_L (N.mm^{-2})	E_R (N.mm^{-2})	E_T (N.mm^{-2})	G_{LR} (N.mm^{-2})	G_{LT} (N.mm^{-2})	G_{RT} (N.mm^{-2})	ρ (kg.m^{-3})
Spruce/rec/1	Mean	12983	2396	958	953	954	137	467
	STD	452	45	51	154	136	26	11
Spruce/rec/2	Mean	19207	2103	637	868	711	114	454
	STD	463	201	61	114	60	9	14
Spruce/age/1	Mean	19008	2129	924	894	754	148	498
	STD	2680	36	169	95	107	28	15
Spruce/age/2	Mean	17852	2294	972	1014	773	118	470
	STD	434	83	34	97	30	22	6

Simulation of different coatings

The application of a surface coatings on one side of the test panel reduces the permeability of the wood surface and leads to different moisture distribution profiles within the panel compared with a simple panel without coating (Figs. 4 and 5). Less moisture penetrates through the coated surface. In the simulation, this is taken into account by reducing the surface emission coefficient for a given surface. Fig. 4 shows the variation of the surface moisture content for different emission coefficients, taken to be between 10 and 100 % of the reference value. The lower the permeability of the coating, the lower becomes the rate of moisture content change of the wood surface and also of the volume underneath (Fig. 5). When there is no coating ($h=h_{ref}$), the panel dries symmetrically from both sides. There is a strong difference to the reference when $h=0.1\ h_{ref}$ and also a significant difference when $h=0.5\ h_{ref}$. After ten days of drying from 50 to 25 % RH, there remains a significant moisture gradient across the panel with a more humid central layer in all cases. In thinner panels, the remaining moisture content after ten days is significantly lower than in thicker panels.

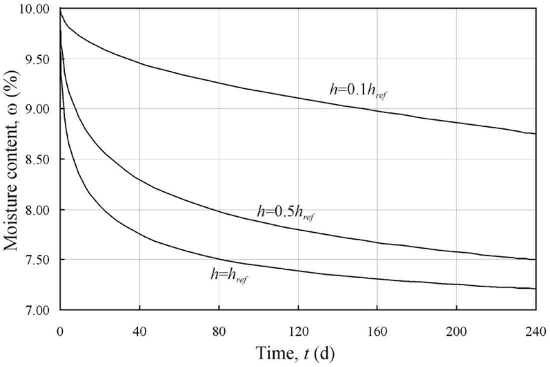

Fig. 4: Simulated moisture content on the surface vs. time for different surface emission coefficients h during drying from 50 to 25 % RH

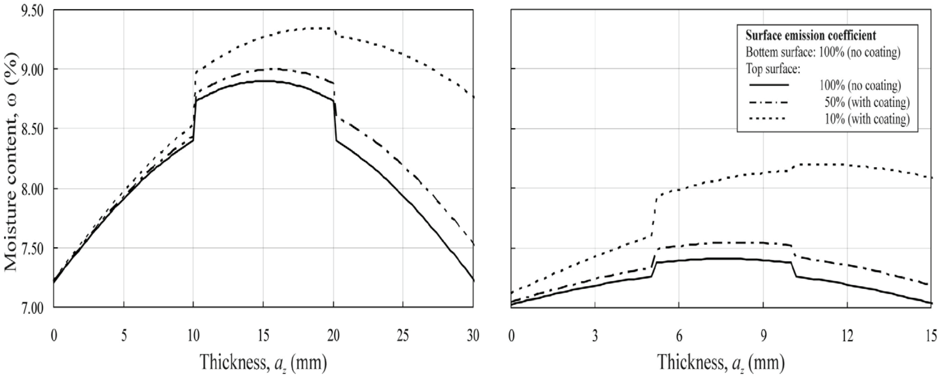

Fig. 5: Simulated moisture profiles within three-layered spruce panels for two different thicknesses (a_z=30mm and a_z=15mm, respectively) and different surface emission coefficients, after 10 days drying from 50 to 25% RH

The resulting calculated deformations are displayed in Fig. 6. The most important deformation is observed for $h = 0.1\ h_{ref}$. In this case the surface without coating dries relatively fast leading to increased shrinkage, whilst the coated opposite surface does not dry as fast and thus experiences less shrinkage. Therefore, the coated side does not counteract the deformation of the more permeable opposite side, and the whole panel bends. Applied to the degradation of cultural objects this would mean that objects carrying a paint or varnish layer only on one face, such as panel paintings, are more at risk than unpainted or uniformly sealed objects.

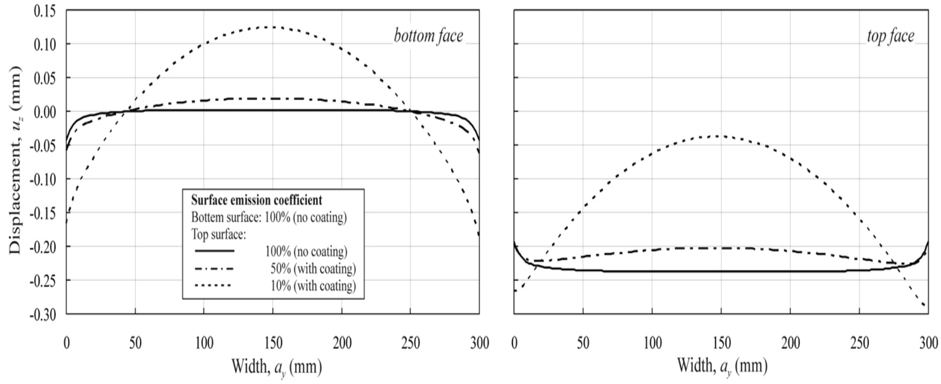

Fig. 6: Simulated displacements in thickness direction, u_z, of 30 mm thick three-layered cross-laminated spruce panels with different moisture permeabilities on both sides

CONLUSIONS

Measurements of the mechanical properties including stiffness and response to RH changes showed no significant influence of the age of the samples. These results showed that naturally aged and recent wood are not inherently different, as long as there are no additional factors present, such as past insect and/or fungal attack, which would have a significant effect on the wood structure and mechanical properties. The results obtained on recent wood are, therefore, in principle transferable to aged material. The same conclusion can be drawn for moisture behaviour of old and new wood.

Previously developed and validated simulation models were applied to the mechanical response on RH variations of cross-laminated panels with different coatings. The results demonstrate that coatings such as varnishes or paint layers, if applied only on one side of the object, potentially aggravate the risk of damage through deformation in unstable environments.

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