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MOISTURE DEPENDENT PHYSICAL-MECHANICAL PROPERTIES FROM BEECH WOOD IN THE MAIN DIRECTIONS

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Abstract

Hardwood is increasingly trying to get established in the building industry in order to realise a larger material output and to take advantage of the superior mechanical properties of hardwood in comparison to softwood for structural applications. For calculations of stress and strain in boards and glued-laminated timbers it is essential to know the specific values of wood in the main directions: longitudinal, radial and tangential. Therefore, the specific values of Young's modulus, shear modulus, Poisson's ratio, the specific values of strength and also these of mass and heat flux (diffusion coefficient, thermal conductivity) were determined on European beech.

Key words: *beech; Young's modulus; shear modulus; strength; orthotropy; visco-elastic.*

INTRODUCTION

Wood is one of the most common building materials used worldwide. Due to its excellent mechanical properties in relation to its weight, it enables the construction of lightweight structures with high strength characteristics. The easy workability, when compared with other materials, makes it an interesting alternative to other competitive but labour-intensive building materials. Moreover, wood is a renewable material, whose availability due to sustainable forestry in Europe, is assured for future generations.

The main drawbacks of wood as a building material arise from its natural origin and are associated with the variability of its properties. This also applies to the mechanical properties, which for wood vary among different species, as opposed to industrially produced materials with homogeneous characteristics. Moreover, depending on the growth conditions, they can also vary within one species. Not surprisingly, the mechanical behaviour of wood has been a topic of research for decades (Kollmann and Côté 1968, Bodig and Jayne 1993, Niemz 1993). However, although the mechanics of wood is known in general, and selected mechanical properties have been presented for a wide range of wood species, several aspects of the mechanical behaviour of wood remain uninvestigated. The mechanical behaviour in the perpendicular to the grain directions (i.e. radial and tangential) in particular, above all the elastic properties, remain the least studied (e.g. Kollmann 1956, Goulet 1980). Moreover, the moisture and time dependency of these properties has so far received marginal attention (e.g. Kufner 1978, Gerhards 1982, Kretschmann and Green 1996).

This certainly applies to European beech wood, the most important hardwood species in Europe. As a building material, beech wood to date plays a subordinate role. While the use of beech wood for applications in load-bearing structures is limited to relatively small amounts, its mechanical properties are actually superior to those of commercially used spruce wood (Niemz *et al.* 2015). For example, tensile, bending and compression strengths of beech wood are about 1.5 times higher and the hardness more than twice as high compared with spruce (Wagenführ 2007). Its excellent strength properties make it suitable for high-performance structural elements such as glue laminated timber beams. Still, the utilisation of beech timber for structural purposes is at present almost negligible: the majority of harvested beech wood is used for energy production. However, it is likely that, due to European silviculture policy and the continuously increasing amount of the standing wood volume of beech in European forests (e.g. 18% of total forest resource in Switzerland with an increasing amount of +4.28 Mio. m^3 within ten years (Brändli 2010)), the potential for better utilisation will increase.

A sustainable use of beech wood resources in future should aim to increase the amount of wood used for structural applications. An indispensable element to achieve this goal is detailed knowledge of the mechanical properties of this species. Available references on the mechanical properties of beech wood, even though they provide a reasonable overview of the mechanical behaviour in general, do not meet the requirements of advanced computational models often used in civil engineering to calculate and predict the properties of structural elements. Sophisticated computational models presuppose knowledge of the mechanical properties with respect to all of the anatomical directions (longitudinal, L; radial, R; tangential, T). Considering the hygroscopic and viscoelastic character of wood, ideally they further require information on the influence of moisture content (MC) and time on the mechanical properties. To date appropriate records of the moisture-dependent mechanical behaviour of beech wood, which also take into account its mechanical anisotropy, are missing. In view of this fact, the only reasonable research line seems the systematic and comprehensive investigation of the mechanical properties of beech wood. The presented research addresses these research gaps.

OBJECTIVE

The goal of the experimentally oriented work was the comprehensive characterisation of the moisture and time-dependent (viscoelastic) orthotropic behaviour of European beech wood (*Fagus sylvatica* L.). The main objective was to explore and document a wide range of material parameters that can be implemented into computational models that allow for advanced simulations of the orthotropic mechanical behaviour of beech wood, taking into account its moisture-dependent and viscoelastic nature.

MATERIALS AND METHODS

The experiments performed in this thesis were carried out on small clear wood specimens from European beech wood (*Fagus sylvatica* L.) grown in Switzerland, near Zürich.

Before testing, tensile specimens (n=10 for each test) were randomly divided into four groups and conditioned in climatic chambers at 30, 65, 85 and 95% relative humidity (RH) at a temperature of 20°C. After the specimens had reached equilibrium MC, uniaxial tensile tests were carried out using a Zwick Z 100 universal testing machine. All tests were performed at standard climatic conditions (65% RH and 20°C). A load cell with 100-kN maximum capacity was used for tensile tests performed in the L direction and a 10-kN load cell for tests in the R and T directions (Fig. 1). The feed rate was defined in such a way that the failure of the specimen would be reached in 90 (±30) s. The strains were evaluated using the digital image correlation DIC technique. A high contrast random dot texture was sprayed on the surface of the specimen to ensure the contrast needed for the evaluation (see middle part of the specimens in Fig. 1). Specimens with similar dimensions have already been successfully applied by Keunecke *et al*. (2008) to determine the tensile Young's moduli and the Poisson's ratios of yew and spruce wood. While a cylindrical shaped specimen is often used to determine the tensile properties of materials, the presented specimen was found to be more appropriate for the measurement of the orthotropic Poisson's ratios.

Calculation of the Young's moduli and the Poisson's ratios

The Young's modulus E was obtained from the ratio of the stress to the strain measured in the linear elastic range. The Poisson's ratio ν_{ij} is defined as

$$\nu_{ij} = -\frac{\varepsilon_i}{\varepsilon_j}, \qquad i, j \in R, L, T \quad \text{and} \quad i \neq j, \tag{1}$$

where: ε_i represents the passive (lateral) strain component and ε_j the active strain component in the load direction. The Poisson's ratio was determined in the linear elastic range from the linear regression of the passive-active strain diagram.

Six shear wave velocities for calculation G-moduli where ultrasonic waves were generated using an off-the-shelf Epoch XT ultrasonic flaw detector using two Staveley S-0104 transducers for transversal waves with a diameter of 12.7 mm were used to carry out the measurements. To ensure coupling between the specimen and the transducers during measurements, a gel-like coupling medium (Ultragel II) was used. Constant coupling pressure during the measurements was guaranteed by the use of a measuring spring (see Ozyhar 2013).

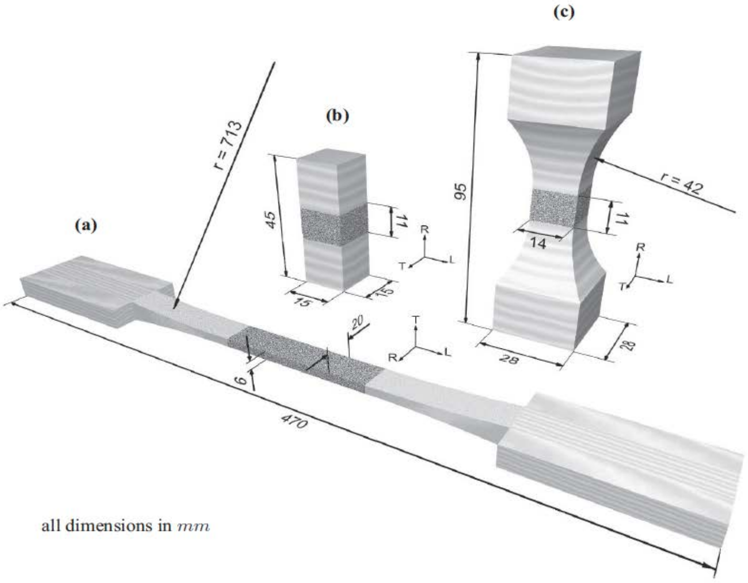

Fig. 1.
Profile and dimensions of specimen with a highly contrasting random dot texture in the cross section used to determine the elastic and strength properties in tension and compression (Ozyhar 2013): a – Specimen according to the DIN 52188 (1979) standard for tensile testing in the L direction (the full specimen dimensions are given in the standard); b – Specimen for the determination of the compressive properties in the L, R and T directions according to DIN 52185 (1976) and DIN 52192 (1979) but lesser in size (example showing a specimen in the R direction); c – "Dog-bone" shaped specimen used to determine the tensile properties in the R and T directions (example showing a specimen in the R direction)

RESULTS AND DISCUSSION

The outcomes of these tests show (Tables 1 and 3, Figs. 2 - 3) that the tensile Young's modulus, shear modulus and tensile strength of beech wood in general increases when MC decreases below the fibre saturation point (FSP). Thereby, the elastic and strength properties in the radial and tangential directions are affected by the MC to a significantly higher level than those in the longitudinal one. Also, the compressive behaviour in general is influenced to a higher degree than the tensile one, which can be deduced from Fig. 4. The highest influence is shown in the longitudinal direction where the tension-compression strength ratio increases from 1,2 at dry conditions to about 2,5 at 16,3% MC. While the stiffness of wood has been proven to significantly decrease with increasing MC, the elastic anisotropy remains widely unaffected by changing MC. In contrast to the above, most of the Poisson's ratios (Table 2, Fig. 2) and also the impact bending strength, which was investigated in a further study (Ozyhar 2013), seem to be moisture independent.

Similar to MC, time history significantly influences the mechanical properties. In additional creep experiments by Ozyhar (2013), time-dependent Young's moduli and Poisson's ratios determined in tension and compression demonstrate that the tensile and compressive viscoelastic behaviour is substantially different, further revealing that the behaviour in the radial and tangential directions is affected by time to a significantly higher degree than that in the longitudinal direction. The diagonal and non-diagonal elements of the viscoelastic compliance matrix demonstrate that the mechanical behaviour of beech depends on the time duration of the mechanical loading.

Table 1

Moisture dependent elastic properties of beech: Tensile Young's modulus (coefficient of variation in brackets) and shear modulus determined by means of ultrasonic waves (Ozyhar 2013)

MC [%]	Young's modulus [MPa]			Anisotropy			MC [%]	Shear modulus [MPa]		
	E_L	E_R	E_T	E_L/E_T	E_L/E_R	E_R/E_T		G_{LR}	G_{LT}	G_{RT}
5,9	12020 *(14,5)*	1800 *(6,7)*	810 *(11,2)*	14,8	6,7	2,2	**9,6**	1370	1010	430
11,3	10560 *(12,5)*	1510 *(8,1)*	730 *(10,3)*	14,5	7,0	2,0	**12,7**	1240	930	380
14,3	9270 *(12,7)*	1340 *(10,3)*	600 *(9,6)*	15,5	6,9	2,2	**16,8**	1110	910	350
16,3	9200 *(19,7)*	1240 *(13,1)*	530 *(6,7)*	17,5	7,4	2,4	**18,7**	980	850	330

Table 2

Moisture dependent Poisson's ratios ν_{ij} of beech; coefficient of variation in brackets (Ozyhar 2013)

MC [%]	ν_{LR}	ν_{RL}	ν_{LT}	ν_{TL} 1)	ν_{RT}	ν_{TR}
5,9	0,04 *(38,2)*	0,43 *(19,5)*	0,04 *(47,3)*	0,59	0,24 *(12,4)*	0,53 *(4,1)*
11,3	0,04 *(42,9)*	0,43 *(17,1)*	0,04 *(41,2)*	0,58	0,31 *(9,8)*	0,61 *(6,7)*
14,3	0,05 *(52,4)*	0,39 *(17,3)*	0,04 *(32,3)*	0,62	0,36 *(8,7)*	0,65 *(7,6)*
16,3	0,04 *(19,3)*	0,47 *(21,2)*	0,05 *(40,4)*	0,87	0,36 *(7,5)*	0,70 *(5,5)*
12,0 2)	0,04	0,37	0,03	0,50	0,33	0,67

1) Calculated values according to equation: $\nu_{TL} = \nu_{LT} \cdot E_L / E_T$

2) Reference values in Bodig and Jayne (1993)

Table 3

Moisture dependent tensile strength in the main directions; coefficient of variation in brackets; σ_{UTS}, ultimate tensile stress; σ_Y, tensile yield stress (at 0,2% plastic strain); ε_{UTS}, ultimate tensile strain (Ozyhar 2013)

	Longitudinal		Radial			Tangential		
MC [%]	σ_{UTS} [N/mm^2]	ε_{UTS} [%]	σ_{UTS} [N/mm^2]	σ_Y [N/mm^2]	ε_{UTS} [%]	σ_{UTS} [N/mm^2]	σ_Y [N/mm^2]	ε_{UTS} [%]
5,9	115,3 *(24,5)*	0,98 *(10,3)*	21,4 *(4,4)*	18,2 *(6,9)*	1,38 *(5,1)*	11,4 *(16,8)*	8,8 *(7,5)*	1,76 *(10,6)*
11,3	96,7 *(28,4)*	1,06 *(19,3)*	19,5 *(9,9)*	14,7 *(15,3)*	1,73 *(12,6)*	8,9 *(18,4)*	7,0 *(6,6)*	1,80 *(27,8)*
14,3	83,6 *(16,9)*	1,13 *(14,2)*	17,1 *(9,5)*	12,5 *(11,5)*	1,99 *(25,4)*	7,8 *(10,3)*	6,1 *(7,7)*	1,89 *(24,6)*
16,3	80,6 *(2,1)*	1,11 *(20,0)*	15,6 *(11,9)*	10,9 *(10,5)*	2,06 *(21,3)*	7,3 *(11,8)*	5,9 *(5,2)*	1,93 *(25,0)*

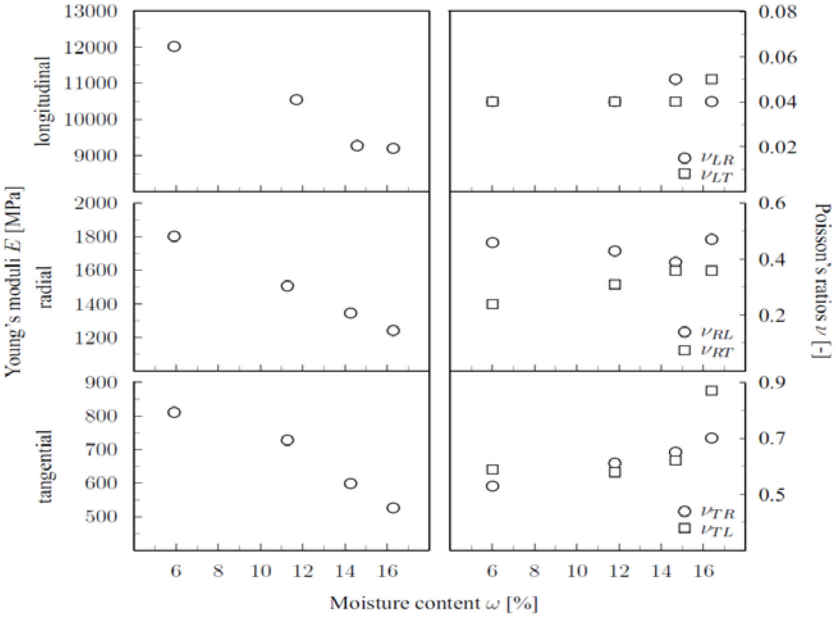

Fig. 2.
Moisture dependent Young's moduli and Poisson's ratios of European beech in tension (Ozyhar 2013)

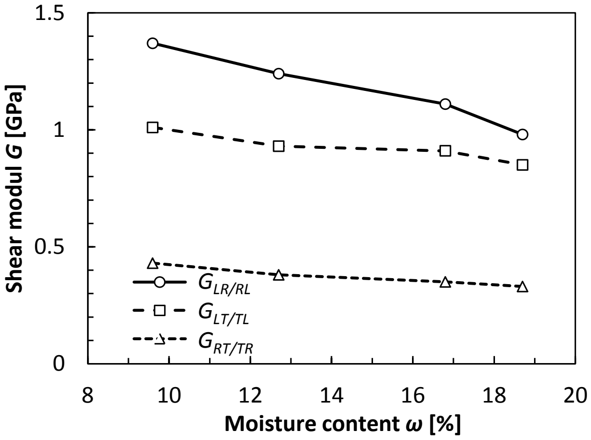

Fig. 3.
Moisture-dependent dynamic shear moduli for beech wood determined by the ultrasonic method (Ozyhar 2013)

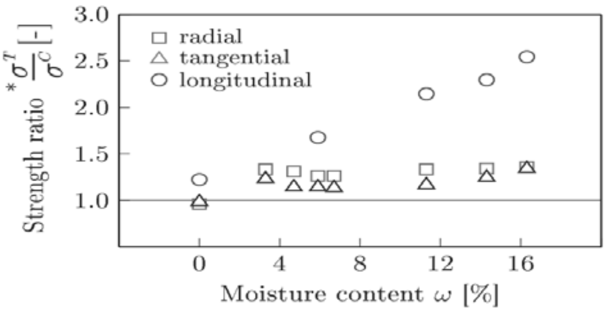

Fig. 4.
Moisture dependent tension-compression strength asymmetry (σ^T/σ^C) for beech (Ozyhar 2013)

CONCLUSIONS

The outcomes of this research show that the elasticity and strength of beech wood in general increases when MC decreases below the fibre saturation point (FSP), while a further increase in MC above FSP does not significantly affect the properties. Thereby, the elastic and strength properties in the radial and tangential directions are affected by the MC to a significantly higher level than those in the longitudinal one. Also, the compressive behaviour in general is influenced to a higher degree than the tensile one. In contrast to this, the impact bending strength and most of the Poisson's ratios seem to be moisture independent. While the stiffness of wood has been proven to significantly decrease with increasing MC, the elastic anisotropy remains widely unaffected by changing MC. Similar to MC, time history significantly influences the mechanical properties. Time-dependent Young's moduli and Poisson's ratios determined in tension and compression demonstrate that the tensile and compressive viscoelastic behaviour is substantially different, further revealing that the behaviour in the radial and tangential directions is affected by time to a significantly higher degree than that in the longitudinal direction.

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