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ORIGINALS ORIGINALARBEITEN

Moisture-dependent, viscoelastic creep of European beech wood in longitudinal direction

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Abstract In the present study, the pure viscoelastic behaviour of European beech wood is analysed in the longitudinal direction at three different moisture contents. The moisture-dependent creep compliance is identified using a four-point bending test device. The viscoelastic behaviour is ascertained to be linear with moisture content and quantified by means of a Kelvin-Voigt model approach.

Viskoelastisches Kriechverhalten von Rotbuche in longitudinaler Richtung bei verschiedenen Holzfeuchten

Zusammenfassung In dieser Arbeit wird das viskoelastische Verhalten von Rotbuchenholz in longitudinaler Richtung bei drei verschiedenen Holzfeuchten untersucht. Mit Hilfe eines Vierpunktbiegeprüfstandes wurde die feuchteabhängige Kriechnachgiebigkeit bestimmt. Ein linearer Zusammenhang zwischen der Holzfeuchte und der Kriechnachgiebigkeit wird nachgewiesen und anhand eines verallgemeinerten Kelvin-Voigt Ansatzes quantifiziert.

1 Introduction

For a numerical simulation of the time-dependent behaviour of wood, viscoelastic material properties are required. Numerous scientific investigations have been carried out considering the time-dependent characteristics of wood and wood composites (Ranta-Maunus 1975; Bazant 1985; Hunt and Shelton 1987; Holzer et al. 1989; Toratti 1992; Liu 1994; Hanhijärvi and Hunt 1998). While basic information about viscoelasticity is given in Nowacki (1965) and Lockett (1972) for example, bending creep tests can be found in Zhou et al. (1999) and Bengtsson and Kliger (2003) or under tensile and compressive load in Toratti and Svensson (2000). Theoretical investigations concerning constitutive laws and models were studied in Kaliske (2000), Svensson and Toratti (2002), Hanhijärvi and Mackenzie-Helnwein (2003) or Fortino et al. (2009).

Moreover, the creep phenomenon can be divided into three types of wood-creep behaviour: the pure, simple viscoelastic or time-dependent creep, the mechano-sorptive creep and the pseudo creep and recovery phenomenon. The latter manifests during continued moisture cycling, the mechano-sorptive is associated with transient moisture content changes and the pure viscoelastic part is a well known phenomenon, however, for wood it requires constant climatic conditions although it depends on the moisture content (Hunt 1999).

Due to the large increase in long-term deformations caused by the interaction of moisture content variations and mechanical loads as well as the increased amount of computational complexity, which is required to solve the time-dependent hereditary integral formulation, the pure viscoelastic creep is usually neglected in numerical models. Thus, the consequence is a lack of systematic experimental data (Liu 1993).

However, the pure viscoelastic creep component is needed not only for a full description of its time-dependent material behaviour in constant climatic conditions, but also for the determination of the mechano-sorptive component. Hence, in this study, the pure viscoelastic creep mechanisms of European beech wood were determined at three different constant moisture contents. The influence of the moisture

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Table 1 Specimen properties of the viscoelastic creep tests at different moisture contents

Tab. 1 Prüfkörpereigenschaften der Kriechversuche bei unterschiedlichen Holzfeuchten

Number of specimen n [–]		Moisture content ω [%]	Density ρ [kg/m^3]
8	$\bar{x}$	8.14	780
	CoV [%]	1.55	2.26
5	$\bar{x}$	15.48	700
	CoV [%]	1.87	7.99
7	$\bar{x}$	23.20	760
	CoV [%]	2.82	2.64

$\bar{x}$ mean value, CoV coefficient of variation

content on the pure creep strain is analysed and quantified by means of a linear regression.

2 Material and methods

2.1 Wood samples

In the present study, the time-dependent deformation behaviour of European beech wood samples (*Fagus sylvatica* L.) from stands near Zurich was analysed.

Samples containing red heartwood, tension wood, knots and other defects were omitted. Cuboid-shaped specimens with dimensions 250 mm × 20 mm × 5 mm (longitudinal–radial–tangential) and orthogonal principal material directions parallel to the edges were chosen with a number $n \geq 6$ annual rings to ensure sufficient reproducibility of material properties in the cross-sectional area. After preparation, the specimens were divided into three groups (Table 1) and climatised at different relative humidities (35%, 80%, and 95%) and at a temperature of 20 °C.

2.2 Experimental setup

After the specimens reached equilibrium moisture content, viscoelastic creep tests were performed on a four-point bending device positioned in a climate chamber.

The bending device was designed for eight specimens with 200 mm distance between the supports. Figure 1 illustrates a section of the experimental design for a single specimen.

The load was applied by means of weights, distributed 30 mm from the centre of the specimen, symmetrically and simultaneously for all eight specimens. Compared to literature references (e.g., Niemz 1993), the average loading of the specimens was approximately 25% of the ultimate bending strength.

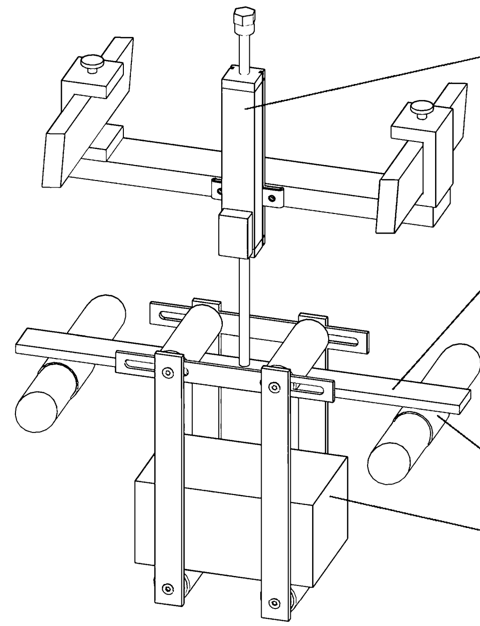

Fig. 1 Arrangement of the specimen in the four-point bending test device (section of a single specimen)

Abb. 1 Probenanordnung im Vier-Punkt Biegeversuch (Ausschnitt einer Probe)

To reduce the influence of friction, the supports were equipped with radial bearings realised by Teflon bushings. The deflections were measured at the deformation maximum by displacement transducers with an accuracy of 0.01 mm.

Additionally, the climatic conditions were monitored by a combined temperature/humidity measuring sensor.

2.3 Compliance analysis

To identify the viscoelastic material characteristic, the measured time-dependent deformations v have to be converted into the stress-strain domain using the compliance function J. Considering the boundary conditions of the four-point bending device, the differential equation for the elastic curve is given by

$$\frac{I v''(x, \omega, t)}{J(\omega, t)} = -M_b(x) \quad (1)$$

including the bending moment M_b and the moment of inertia I, which are used to calculate the total compliance $J(\omega, t)$. It has to be noted that this simplified approach is used with the specimen slenderness taken into account, apparent shear stresses neglected and with only small gradients in the displacement expected.

For a characterisation of the viscoelastic material properties, the total compliance function $J(\omega, t)$ was determined at three different moisture conditions. Subtracting the initial pure elastic part of the compliance J_0 and fitting the data to a generalised Kelvin-Voigt model with a term for a linear moisture dependency

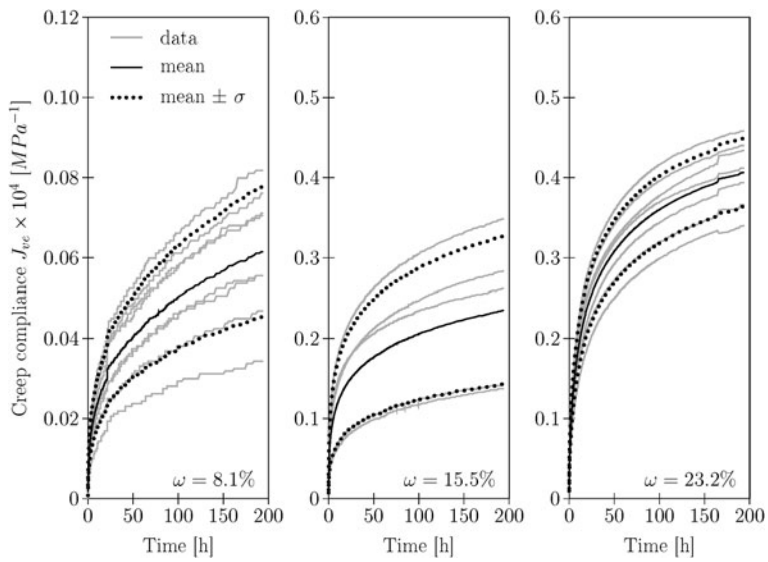

Fig. 2 Measurement data of the moisture-dependent creep compliance of European beech wood in the longitudinal direction
Abb. 2 Messdaten der holzfeuchteabhängigen Kriechnachgiebigkeit von Rotbuchenholz in longitudinaler Richtung

$$J_{ve}(\omega, t) = J(\omega, t) - J_0(\omega) = \sum_{r=1}^{m} (J_{r_1}\omega + J_{r_0})\left(1 - e^{-t/\lambda_r}\right) \quad (2)$$

yields the viscoelastic compliance function J_{ve}.

3 Results and discussion

The measurement data with mean and standard deviation curves and the corresponding fitted creep compliance function are visualised in Figs. 2 and 3. The approximation, except for some minor deviations at the beginning, is in good agreement with the mean values of the measurement data. Hence, results from the measurements of this study suggest a linearly increasing viscoelastic compliance function with increasing moisture content.

Table 2 provides the parameters of (2), which were determined using $m = 6$ Kelvin-Voigt elements with the method of least squares.

However, such a compliance function is thermodynamically admissible if thermodynamic laws are satisfied (Dubois et al. 2005). Besides positive values of the compliance function $J(\omega, t) \geq 0$ as well as its derivative $\partial J(\omega, t)/\partial t \geq 0$, every Kelvin-Voigt element has to fulfil specific thermodynamic restrictions. On the one hand, the relaxation times λ_r obviously have to be positive, which is given without exception. On the other hand, the element compliances $J_{r_1}\omega + J_{r_0}$ have to be positive as well, which cannot be achieved for all six elements and moisture contents (cf. Mohager and Toratti 1992; Liu 1994). A regression analysis performed on the constraint of positive element compliances, however, yields (even with an increased number of Kelvin-Voigt elements ($m = 20$)) no results comparable to the latter. Hence, the proposed approach is used, even though it is more descriptive than a mechanical approach. Nevertheless, the results allow for a representation of the measured material behaviour and comparison against other species and other creep components.

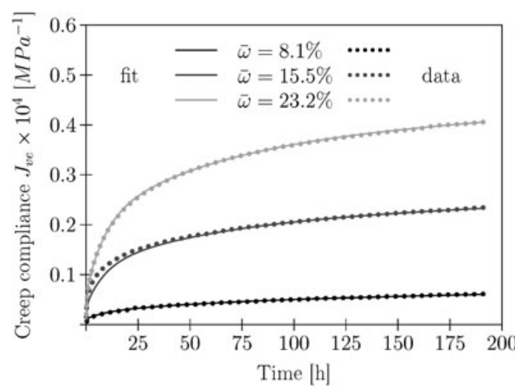

Fig. 3 Measurement data vs. fitted creep compliance function depending on time and moisture content for European beech wood in the longitudinal direction
Abb. 3 Vergleich der Messdaten mit dem Regressionsmodell der zeit- und feuchteabhängigen Kriechnachgiebigkeitsfunktion für Rotbuchenholz in longitudinaler Richtung

Here, it has to be noted that a different number of specimens are assigned to inner defects of the specimen, due to the fact that arising outliers show no significant differences in density, ultrasound velocity, number of annual rings, orientation of the principle axes and moisture content.

The obtained material parameters are determined for moisture contents in between $\omega \cong 8, \ldots, 23\%$ and up to a time $t \cong 200$ h. For this reason, terms and conditions of usage and even extrapolation should be handled with care.

Table 2 Regression coefficients of the moisture- and time-dependent creep compliance $J(\omega, t)$ of European beech wood in the longitudinal direction

Tab. 2 Regressionskoeffizienten der feuchte- und zeitabhängigen Kriechnachgiebigkeit $J(\omega, t)$ in longitudinaler Richtung für Rotbuchenholz

r [–]	J_{r_1} [MPa^{-1}]	J_{r_0} [MPa^{-1}]	λ_r [h]
1	−7.69e-7	3.74e-6	1.11
2	1.11e-6	−4.99e-6	0.82
3	9.84e-7	−5.22e-6	60.86
4	8.51e-7	−5.97e-6	8.90
5	2.82e-6	1.03e-5	3427.65
6	5.06e-7	−2.90e-5	7039.80

4 Conclusion

The presented material data not only indicates viscoelastic creep behaviour linear to the moisture content, but also provides a moisture-dependent set of input data for subsequent time-dependent numerical analyses of European beech wood structures. Moreover, essential material parameters for further quantification of the mechano-sorptive material behaviour were obtained and a promising equation for descriptive material characterisation was introduced.

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