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Experimental and Numerical Analysis of the Long Term Behaviour of Glued Laminated Timber

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Abstract

In this paper the results of the experimental and numerical analysis of the long term behaviour of glued laminated timber in a sheltered outdoor environment are presented. The tests on six loaded and five unloaded glulam beams were initiated in the summer of 2003 and finished in autumn of 2006. The temperature, relative humidity, displacements and strains were measured at hourly intervals. The numerical procedure was divided into two physically separated but closely related phases. In the first phase coupled problem of moisture and heat transfer over the timber beam were numerically solved using the enhanced finite element method. The results of the first computational stage were used as the input data for the numerical analysis of mechanical response of glulam elements.
This paper presents some comparisons of the relevant measured and calculated quantities.

Keywords: long term tests, heat and mass transfer, timber structures, glulam elements, multi-Fickian moisture transfer, temperature dependency.

1 Introduction

Wood is in general an open porous hygroscopic material. Being such, the changing climatic conditions of natural environment effect on behaviour of material and timber structures. The influence of changing climate condition on wood are in general known and many investigations of rheological behaviour of real sized wood and wood based products relating to shrinkage and swelling, viscous creep and mechano-sorptive effect have already been performed [1, 2]. However the majority of creep tests were carried out at high level bending stresses up to 15 MPa [1] since the deformations and deflections are easier to register. On the contrary, stress level caused by application of permanent loads are in general much lower. Our aim was to obtain the results for glue laminated timber beams produced from unprotected

Slovenian spruce, installed in outdoor sheltered environment in Slovenia and loaded in such a manner that the most common stress range would occur in elements. This would extend the available datasets on rheological behaviour of wood and furthermore present reliable database for calibration and evaluation of proposed numerical solution of coupled problem of moisture and heat transfer over the glue laminated timber.

2 Experiment

One of the most common applications of glue laminated timber elements are simple supported beams installed in sheltered environment. In most applications beams are protected from direct sunlight which may have significant influence on discussed wood behaviour. However, direct insolation is difficult to model and in order to eliminate the effect additional protection was installed from south and east side. Beams were also protected from direct impact of snow and rain without any relevant effect on air circulation around the specimens (Figure 1).

Figure 1: Sheltered outdoor environment (left) and test setup (right).

Glulam beams 0.05 x 0.10 x 1.80 m made from non-treated Slovenian spruce and glued with the RFF glue were installed as simply supported beams on a wooden substructure (Figure 1). Supports were made from zinced steel (Figure 1 and 2). Five specimens were not loaded (marked as N1-N5) and six loaded (L1-L6) with relatively low stress level (compared with the bending strength of specimens). Load (2 x 1.52 kN) was applied with concrete blocks in two points (one third and two thirds of the span (Figure 13)). Additional samples were installed in order to implement simple non-destructive gravimetric method [3]. The test setup was installed at the outdoor testing facilities at Slovenian National Building and Civil Engineering Institute.

The following quantities were recorded on loaded beams at hourly intervals form June 9th 2003 to October 12th 2006: vertical displacements in the middle of the span (LVDTs), horizontal displacements at the free end (LVDTs), longitudinal strains – top and bottom lamella (strain gauges) – all beams, longitudinal strains (beam L6) – second top, middle, second bottom lamella (strain gauges) and transverse strains (extensometers). On beams which were not loaded the following quantities were measured during the same period: horizontal displacements (LVDTs) at the free end, longitudinal strains (beam N1) – top, middle and bottom lamella (strain gauges) and transverse strains (extensometers) (Figure 2). Temperature and MC were measured at three locations. Detailed description of measuring points and procedure is given in [4].

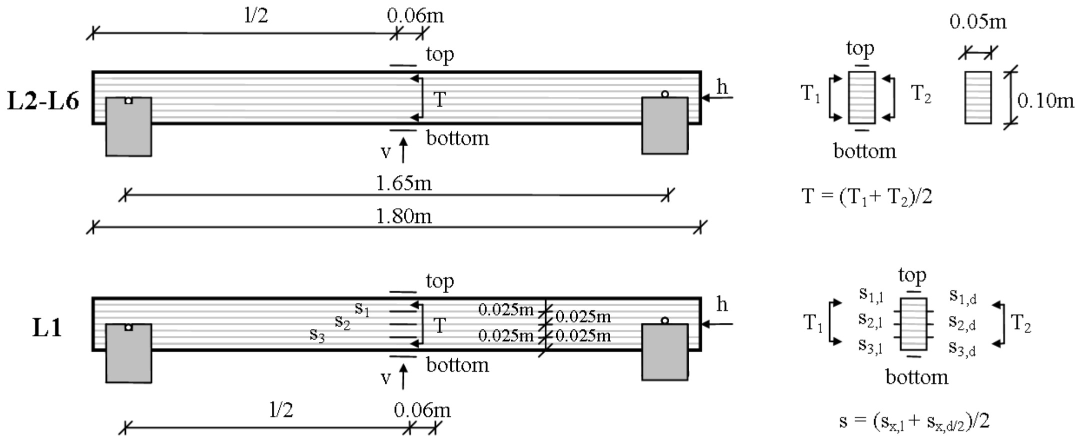

Figure 2: Supports and measuring points [4].

Figure 3: LVDTs, extensometers and MC measuring sensors.

The experiment and results were already presented in [4] and [5]. Therefore, only the relevant measuring results for the whole testing period and conclusions are presented.

The measurement database was – due to the long term testing and due to the number of measuring points –filtered and checked from quantitative point of view. All clearly deviating values were excluded form the measurement database.

The environmental conditions present the basic data for any modelling of wood under changing environmental conditions. Results obtained in two measuring points were practically equal. Clear year cycles can be observed on the time- temperature and time- RH diagrams (Figure 4, 5).

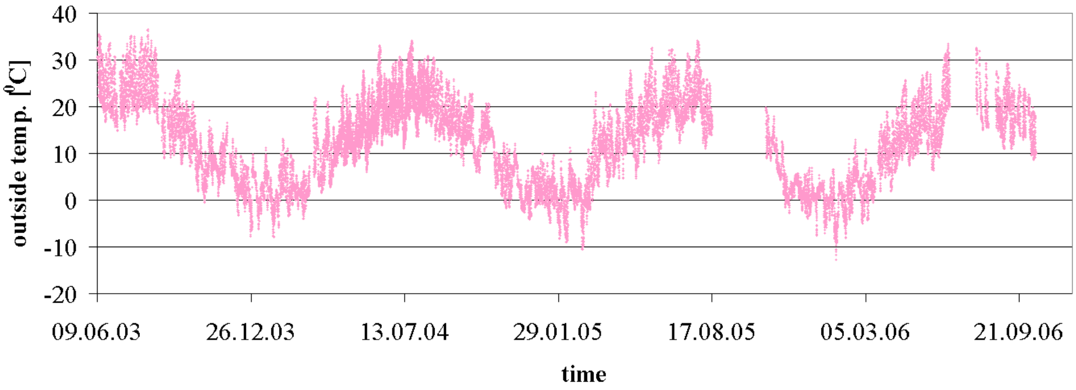

Figure 4: Air temperature.

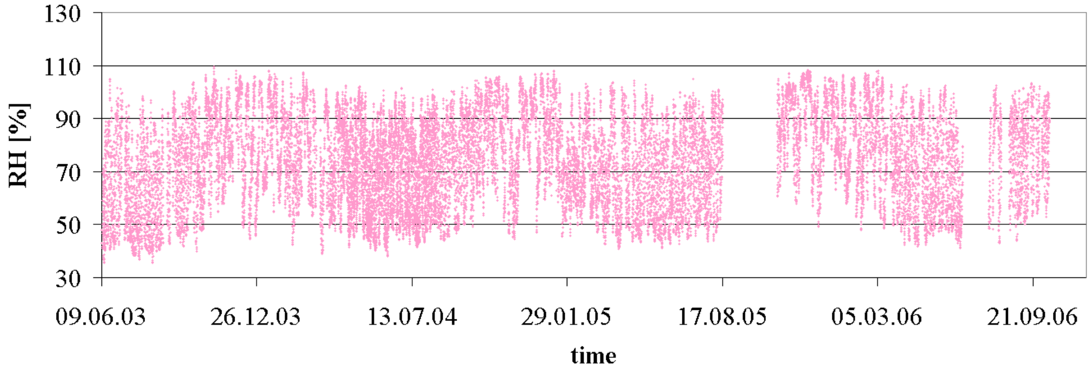

Figure 5: Relative air humidity.

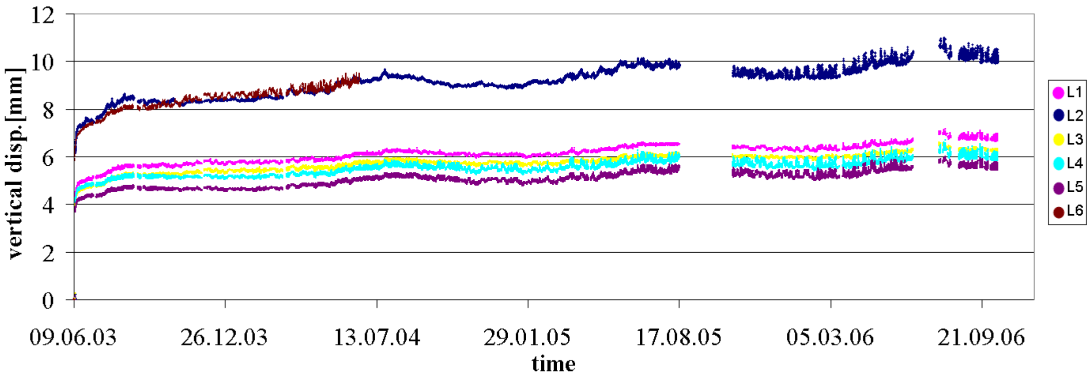

Figure 6: Loaded beams, vertical displacements at mid span.

The diagrams of the mid span vertical displacements, presented in Figure 6, indicate differences in mechanical characteristics of beams. If values are normalized there are is no evident difference between specimens. Identification of differences was additionally confirmed by mechanical tests preformed after long term tests. On all specimens mechanical tests according to EN 408 were performed: local MOE, global MOE and strength were measured (Table 1). The diagram (Fig. 6) indicates that the majority of vertical deformations occur in the first month or two after imposing a load. Furthermore, vertical displacements increase during year cycles can also be observed. Increase of displacements in the summer is more intensive than in the winter.

beam	ρ_{glulam} [kg/m^3]	MOE [N/mm^2]	Strength [N/mm^2]
L1	477	13781	54.9
L2	436	10220	39.3
L3	528	14549	50.5
L4	516	15514	62.3
L5	525	15813	69.5
L6	416	10401	36.7
N1	490	13251	43.5
N2	509	13709	55.4
N3	442	11733	37.2
N4	490	12049	42.0
N5	436	11854	47.9

Table 1: Mechanical characteristics of beams

Differences in horizontal displacements of loaded beams at free ends are also present, but not so evident. With the diagrams of horizontal displacements year cycles can be clearly identified which is expected since the temperature and shrinkage induced by changing water content are the main reasons for the extension of the beam.

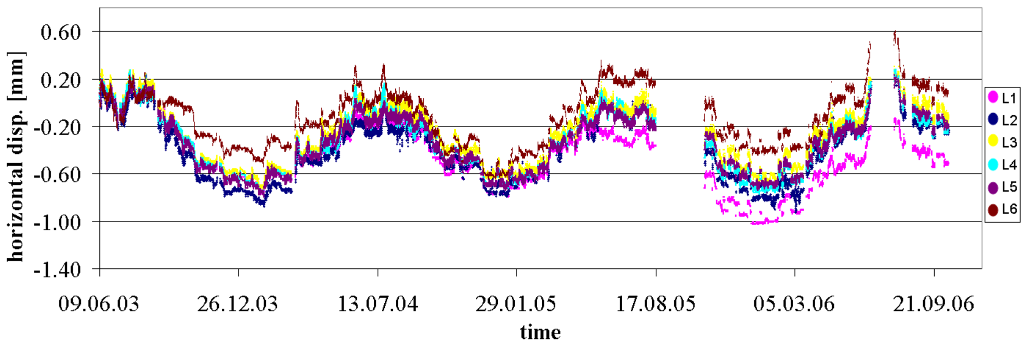

Figure 7: Loaded beams, horizontal displacements.

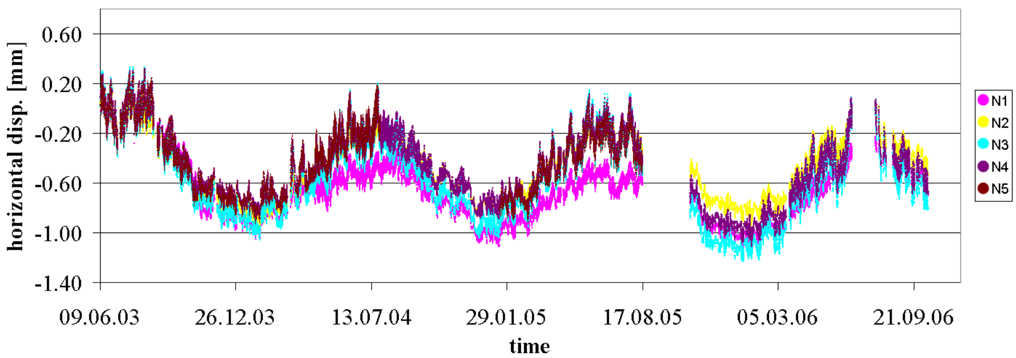

Figure 8: Non loaded beams, horizontal displacements.

3 Numerical solution

Mechanical behaviour of timber elements is very complex phenomenon where the temporal and spatial distribution of temperature and water content of wood plays a decisive role. The deformation of the structure does not significantly affect the moisture and heat transfer. Therefore, the numerical procedure is divided into two physically separated but closely related phases. In the first phase the time development of the moisture and temperature state of the timber element is calculated. The results of the first computational stage are used as the input data for the numerical analysis of mechanical response of glulam elements.

3.1 Moisture and temperature state of timber

Water and heat transport over the beam is modelled by a coupled multi-Fickian transport model presented in [6]. The vapor transport in pores and the bound water transport in wood tissue are modelled by a system of two individual transport equations both following Fick's law as:

$$\frac{\partial c_b}{\partial t} = \nabla\ \left(\mathbf{D}_b \nabla c_b + \mathbf{D}_{bT} \nabla T\right) + \dot{c} \tag{1}$$

$$\frac{\partial}{\partial t}\left(p_v \frac{\varphi M_{\mathrm{H_2O}}}{RT}\right) = \nabla\ \left(\mathbf{D}_v \nabla \left(p_v \frac{\varphi M_{\mathrm{H_2O}}}{RT}\right) + \mathbf{D}_{vT} \nabla T\right) - \dot{c}, \tag{2}$$

where c_b and p_v are the concentration of bound water in cell wall and partial vapor pressure in cell lumen irrespectively. Matrices $\mathbf{D}_b$ and $\mathbf{D}_v$ contain diffusion coefficients of bound water and water vapor, similarly $\mathbf{D}_{bT}$ and $\mathbf{D}_{vT}$ are corresponding thermal coupling diffusion matrices, T is the temperature, φ is the porosity, $M_{\mathrm{H_2O}}$ molecular mass of water, R the universal gas constant and $\dot{c}$ is the sorption rate. All the diffusion coefficients in eqs. (1-2) are temperature dependent. Their relationships are given in [6].

In the transport process bound and vapor water interact by a process known as sorption. It describes process of phase change from vapor to bound water and vice versa. Process of sorption slows down at higher relative humidities and is hysteretic. Temperature dependency of these phenomenon (adsorption and desorption curve) is considered according to the [6], while sorption process is described with sorption hysteresis model given in [7].

The third equation is the energy conservation equation.

$$\left(c_b C_b + c_v C_v + c_v C_0\right)\frac{\partial T}{\partial t} + \left(h_b - h_v\right)\dot{c} + \left(C_b \mathbf{J}_b + C_v \mathbf{J}_v\right)\nabla T = \nabla\ \left(\mathbf{k}_{\mathrm{mix}} \nabla T\right) \tag{3}$$

There T is the temperature, C_α is the specific heat capacity of the α-component of the mixture, h_b and h_v are the enthalpy of the phases (bound water and water vapour), $\mathbf{J}_b$ and $\mathbf{J}_v$ mass fluxes of the phases, $\mathbf{k}_{\mathrm{mix}}$ the thermal conductivity of the timber. Furthermore, the homogeneity of material properties across the cross-section is assumed.

Terms on the left side of eq. (3) present accumulated energy, sorbtion and diffusion whereas term on the right side present transport of energy by conduction. The third term on the left hand side is the background for the so-called Dufour effect, i.e., transport of heat by mass transport of molecules with a given enthalpy.
In eq. (3) the specific energy content is expressed in terms of concentration of the individual component, its specific heat capacity and the common temperature of the components (Figure 9). Furthermore, the energy released or consumed by the phase change from water vapor to bound water is included in the balance.

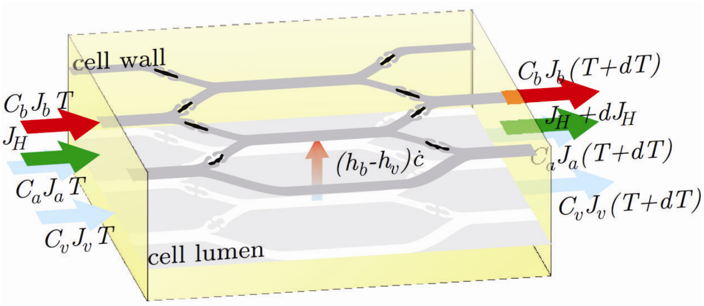

Figure 9: Various paths for transport of heat in the cellular structure of wood [5].

Bound water concentration c_b partial vapor pressure p_v and temperature T, are three basic variables of the equation system for moisture and heat transport (eq. 1-3). These equations with corresponding initial and boundary conditions are generally non-linear and can be rarely solved analytically. Therefore, numerical methods have to be employed. In our case the computer program based on finite element method, presented in [8] was used and extended to include heat transfer. It is assumed that the partial vapor pressure at the (imaginary) boundary between surrounding air and pores (lumens) at a macroscopic surface p_v^s is identical to the partial vapor pressure of ambient air p_v^a. Therefore Dirichet boundary condition is applied:

$$p_v^s = p_v^a. \tag{4}$$

Additional bound water can only be added to the system by adsorption. Since bound water is restricted to wood, it is obviously not moving through the surface, and the Neumann boundary condition is applied:

$$\mathbf{n} \cdot \mathbf{J}_b = 0, \tag{5}$$

where $\mathbf{J}_b$ is the bound water flux and $\mathbf{n}$ is the normal vector to the cell wall surface. Heat transfer at the boundary is prescribed with the Neumann boundary condition.

$$\mathbf{n} \cdot \mathbf{J}_T = -\mathbf{k}_{\text{mix}} \nabla T \tag{6}$$

where $\mathbf{J}_T$ is the heat flux at the surface.

3.2 Mechanical analysis

The basic assumption in mechanical analysis of beam elements is that imaginary longitudinal filaments of an element are exposed to uniaxial stress state. This assumption significantly facilitates the task because the results of uniaxial tests can be directly used for the formulation of constitutive relations.

In order to consider the geometrical and material non-linear behavior of an element, the relation between strain ε moisture c_b longitudinal normal stress σ and time t are expressed in an incremental form:

$$\mathrm{d}\sigma = \mathrm{d}\sigma\left(\sigma_0, \varepsilon_0, c_{b0}, \mathrm{d}\varepsilon, \mathrm{d}c_b, \mathrm{d}t\right). \tag{7}$$

In this work, the additive principle is adopted where the total geometrical strain increment $\mathrm{d}\varepsilon$ is expressed as a sum of shrinkage/swelling $\mathrm{d}\varepsilon_\mathrm{s}$, normal creep $\mathrm{d}\varepsilon_\mathrm{c}$, mechano-sorptive $\mathrm{d}\varepsilon_\mathrm{ms}$ and mechanical strain increment $\mathrm{d}\varepsilon_\mathrm{m}$. Due to incremental approach and assuming that all the values involved are sufficiently small, in our numerical evaluation, the infinitesimal stress and strain increments as well as the increments of water content and time are replaced by the finite ones and additive principle can be written as:

$$\Delta\varepsilon = \Delta\varepsilon_\mathrm{s} + \Delta\varepsilon_\mathrm{c} + \Delta\varepsilon_{ms} + \Delta\varepsilon_\mathrm{m}. \tag{8}$$

Shrinkage and swelling deformations are assumed to be a linear function of water content. Thus, the increment of shrinkage/swelling deformation is:

$$\Delta\varepsilon_\mathrm{s} = \alpha_\mathrm{s}\Delta c_b, \tag{9}$$

where α_s is a constant shrinkage coefficient parallel to the grain at the actual constant temperature. Normal creep depends on the time only, i.e., the changes of moisture content have no effect on normal creep. Various creep models for wood can be found in the literature. In this study next model is used where the increment of normal creep is:

$$\Delta\varepsilon_\mathrm{c} = \sigma_0 a_1\left(e^{-a_2 t_1} - e^{-a_2 t_0}\right), \tag{10}$$

where σ_0 is the stress at the beginning t_0 of the time step $\Delta t = t_1 - t_0$, a_1 and a_2 are model parameters. The increment of mechano-sorptive deformation is expressed by

$$\Delta\varepsilon_\mathrm{ms} = \sigma_0\Phi^\infty\left(1 - e^{-c\Delta c_b}\right), \tag{11}$$

where c is generally different for sorption and desorption and Φ^∞ is the reference compliance.

The mechanical part of the deformation consists of an elastic part $\Delta\varepsilon_\mathrm{e}$ only, i.e., the plasticity effect is negligible due to relatively low level of stresses and does not explicitly depend on time and water content. It is obtained from eq. (8) as:

$$\Delta\varepsilon_\mathrm{m} = \Delta\varepsilon_e = \Delta\varepsilon - \Delta\varepsilon_\mathrm{s} - \Delta\varepsilon_\mathrm{c} - \Delta\varepsilon_{ms}. \tag{12}$$

Based on Hooke's law, the increment of elastic strain can also be expressed by

$$\Delta\varepsilon_{\mathrm{e}} = \frac{1}{E_1}\left(\Delta\sigma - \Delta E\varepsilon_{\mathrm{e}0}\right). \tag{13}$$

Here, subscripts 0 and 1 denote the quantities at the beginning and at the end of the time step, respectively. By comparing the eqs. (12) and (13), the stress increment $\Delta\sigma$ can be expressed in a simple form

$$\Delta\sigma = E_1\Delta\varepsilon_{\mathrm{e}} + \Delta E\varepsilon_{\mathrm{e}0}. \tag{14}$$

Stress σ_1 at the end of the time step is

$$\sigma_1 = \sigma_0 + \Delta\sigma. \tag{15}$$

Eqs. (8-15) represent a specific constitutive model which was incorporated into the self-developed computer program which works in MatLab environment. The solution of the coupled boundary value problem is calculated numerically by partial differential equation solver in MatLab. Original code is appropriately modified to be used with hysteresis model and solve the problem of heat and moisture transport in wood.

4 Numerical example

The aim of this study was to present the spatial and time development of temperature and moisture content and also the mechanical behaviour of glulam beam exposed to varying outside ambient conditions. Results are compared with those measured during the experiment. In this analysis we consider first 192 days of the experiment period to present the capability of the before presented numerical model, while whole experiment lasted more than 2 years.

4.1 Results of moisture and temperature state of timber

The numerical values of the material parameters, used in the numerical calculations, for the constitutive relation and the governing equations are taken from the literature [6-8]. Reduction factor ξ_T is 0.4 and diffusion coefficient D_T is 17.5 x 10^{-6} $\mathrm{m}^2\mathrm{s}^{-1}$.

The beam consists of seven laminations. The glue between laminations is considered as an impermeable barrier for the moisture flow which represents an extreme assumption about the glue permeability. Assuming this, numerical simulation can be made for only one lamination of the cross-section that is exposed to the outside change of relative humidity (RH) and temperature. The time development of the moisture content in the point at the distance of 10 mm from the outside boundary is presented in Figure 10.

We can observe extensive local daily variation of the moisture content in the first 50 days. At around day 50 quite big sudden increase of the measured moisture content occurred. Afterwards measured moisture content drops again down quite rapidly to around 18%. This measured values leaves out doubts on the accuracy of the moisture measurements around this period. Anyway the calculated daily amplitude variation is on average around 3% and very well agrees with one from the experiments.

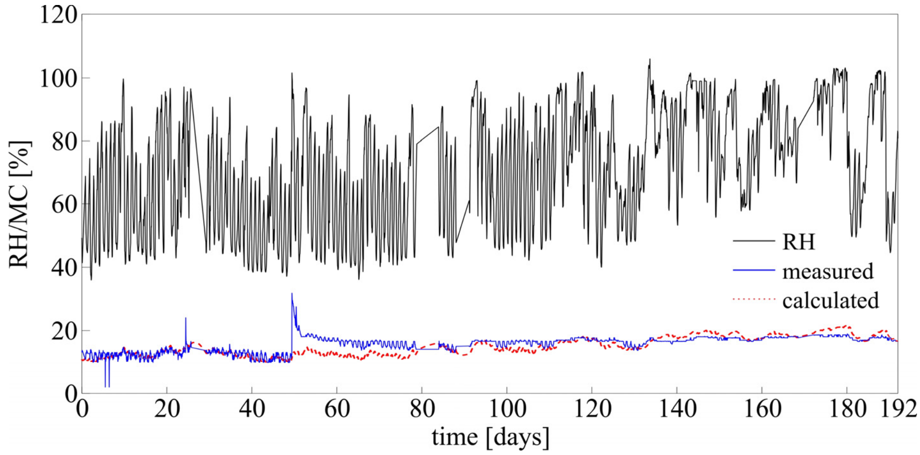

Figure 10: Moisture content development in the point at the distance of 10 mm from the outside boundary of the middle lamination of the glulam beam for 192 days.

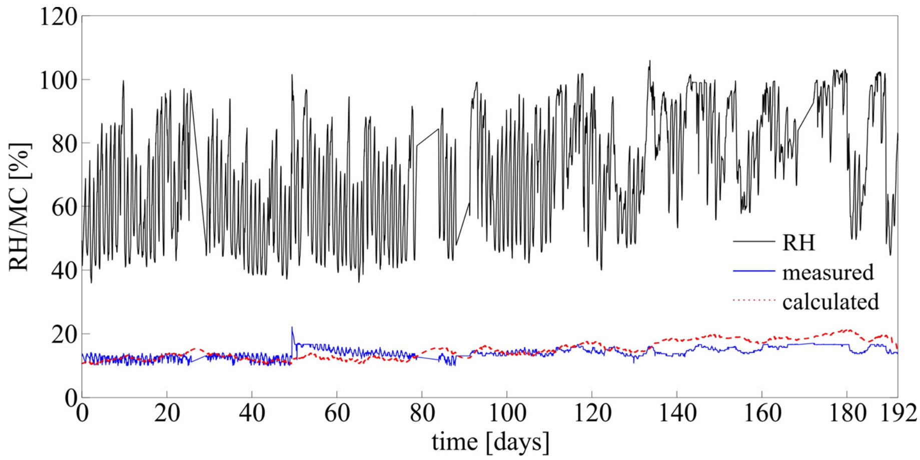

Figure 11: Moisture content development in the centre point of the middle lamination of the glulam beam for 192 days.

Similar behaviour of the moisture content distribution can be noticed on Fig. 11 where the time development of the moisture content in the centre point is presented. Here slightly bigger difference in average value of the moisture content from day 130 onward can be noticed. Figure 12 shows that measured and calculated values of temperature in the centre point of the middle cross-section of the beam are in good agreement.

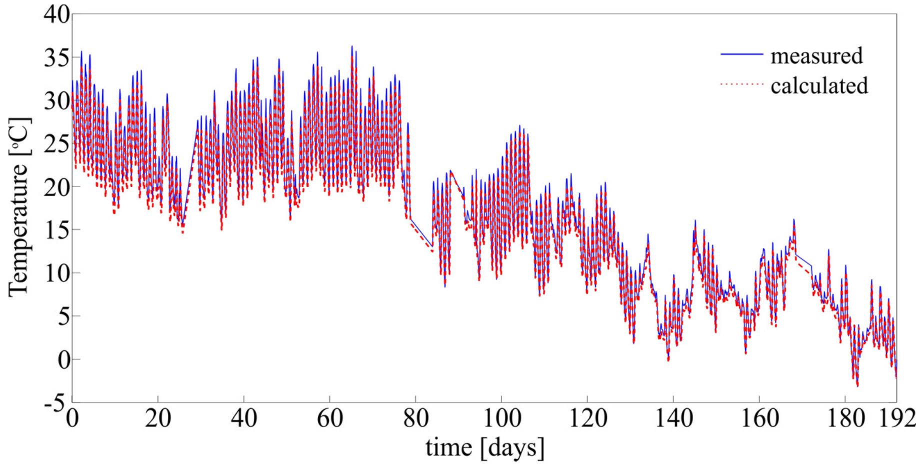

Figure 12: Temperature development in the centre point of the middle lamination of the glulam beam for 192 days.

4.2 Results of the mechanical analysis of the glulam beam

The geometry and the mechanical load are shown in Fig. 13.

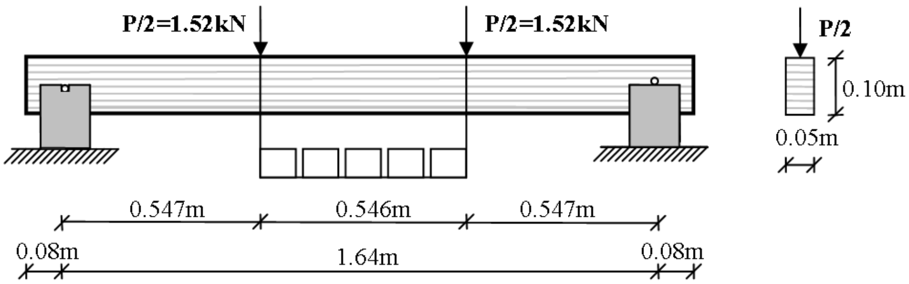

Figure 13: Loading schema.

The water content distribution presented in previous section was used as input data for mechanical analysis. Mechanical analysis was performed for the glulam beam marked as L3 in the experiment. The material parameters are shown in Table 2.

Parameter	Value
Elastic modulus	$E_{ref} = 1450$ kN/cm^2
Shrinkage parameter	$\alpha_s = 6.25 \times 10^{-5} / c_b$ %
Mechano-sorptive parameter	$\Phi^{\infty} = 0.00003$
Mechano-sorptive par. (sorption)	$c^+ = 1.6$
Mechano-sorptive par. (desorption)	$c^- = 2.4$

Table 2: Material parameters used in numerical simulation

In Table 3, the values of the parameters of the creep model used for the mechanical analysis are shown.

Parameter	α_1 (x10^{-3})	α_2 (x10^{-2})
Tension	−2.719	1.975
Compression	−1.85	2.017

Table 3: Creep parameters for the creep model

At first the parametric study of the influence of shrinkage and swelling, mechano-sorptive and normal creep deformation on mechanical response of beam is presented. The results of analysis are time dependent vertical displacement curves in mid-span of glulam beam shown in Figure (14).

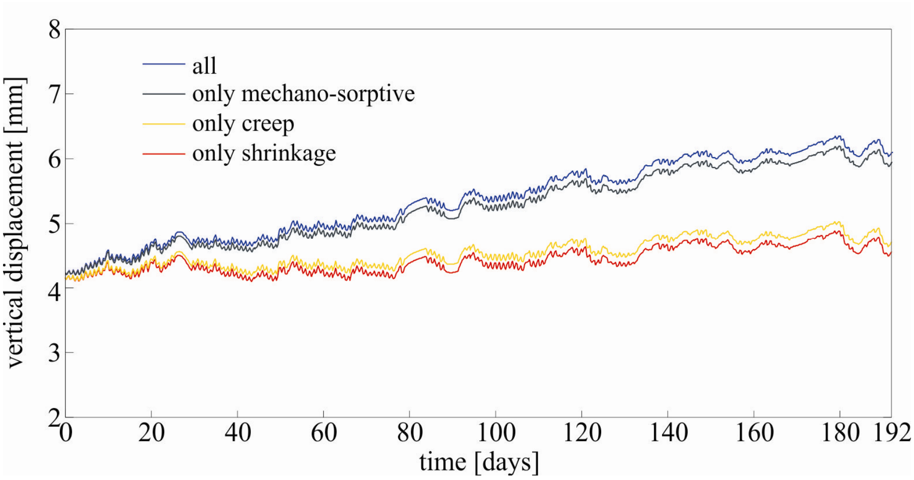

Figure 14: Vertical displacements in the middle of span, loaded beams L3 for different deformations considered.

Four different curves are presented, where for example curve “only creep” is calculated by considering only normal creep deformation in Eq. (12), other types of deformations were neglected. With parameters chosen in accordance with tables 2 and 3, the main influence on vertical displacements have mechano-sorptive and normal creep deformations, whereas shrinkage and swelling have smaller impact on vertical displacements. The results have to be used with caution because they are directly dependent of parameters given in tables 2 and 3. Parameters are calibrated for climate conditions which appeared in experimental study. Therefore, new calibration will have to be done in the cases of different climate conditions.

Displacements at the mid-span of the beam obtained by numerical simulation were compared to displacements obtained by the experiment (Fig. 15). At the beginning up to 80 days the numerical displacement is lower than the one from experiment. Afterwards the experimental displacement somehow stabilizes and the global increase of the mid-span displacement is relatively small, while the calculated value of the mid-span displacement still rises up to day 130 before it start to stabilize and at the end it is larger than experimental value. If we look back at the results of the moisture content we can notice that after 80 days numerical values of moisture content are bigger than experimental one. Therefore such numerical results of the mid-span displacement are somehow expected. However, numerical and experimental results in general prove that the influence of shrinkage, creep and mechano-sorptive effect on real timber structures is significant in the early phase of the constant permanent loading. It was found that mechano-sorptive and creep parameters have important impact on the numerical result. Values given in Table 2 and 3 were obtained by parametric study.

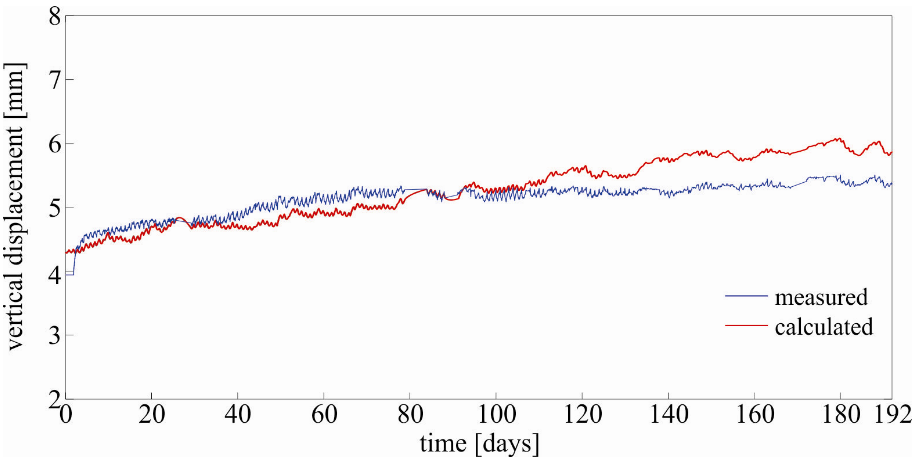

Figure 13: Vertical displacements in the middle of the span, loaded beam L3.

5 Discussion and conclusions

Although the number of specimens in the presented experiment was relatively low, the test results in general confirm that at the stress level applied the influence of shrinkage, creep and mechano-sorptive effect on real timber structures is important in the early phase of loading. However, these effects become almost negligible after relatively short period of time. For the case of beam L3 this time period was around 50 days. The dependence of elastic modulus on water content and temperature remains an important parameter which determines the deformability of beams. The main problem in mechanical analysis remains the experimental evaluation and verification of parameters involved in numerical procedures. It turns out that mechano-sorptive and creep parameters have major impact on the numerical results.

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