Behaviour of creep of timber beams under natural environmental conditions

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Abstract

The current research is devoted to the investigation of relationships in creep behaviour of timber beams under natural environmental conditions with the purpose of detecting the factors significantly affecting such parameters as the variable moisture content of wood, temperature, stress level, span-depth ratio, macrostructure of wood and other factors, and to establish a mathematical model applicable for determining parameters related to prognosis of deflection of timber beams under variable loads. This study includes the analysis of experimental test results in static bending of 17 softwood (*Pinus Sylvestris* L.) beams with different span and span/depth ratios regarding a variation of moisture content, relative humidity and air temperature. The mathematical model examined in this study for the description of creep has been developed on the basis of the Burger body concept. A sufficiently good compatibility of average experimental and modelled strain values of timber beams was observed in the results. These results testify that the developed creep model may be used for predicting deformation of timber beams, and constants involved are applicable for natural environmental conditions. This study is part of extensive research that is aimed at contributing to the determination of accurate model parameters and to establishing an adequate and practically applicable mathematical model for more accurate predictions of final deflection of timber beams for design purposes.

Keywords: timber beams, deflection in bending, development of creep under natural environmental conditions, mathematical model of creep.

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1 Introduction

The prognosis of the long-term behaviour of timber structures under service loads and environmental influence is one of the most discussed issues in research and design of timber structures since deformations develop due to very complicated physically mechanical time-dependent effects influenced by a wide range of factors, such as variable moisture and temperature conditions, stress level, span-depth ratio, the structure of wood per se and other factors that should be taken into consideration when predicting deformations of timber structures more accurately for design purposes.

There have been a lot of serious investigations devoted to load duration (DOL) effects in wood carried out by researchers in different countries up to now, and more extensive reviews on the topic have been written by Morlier [1], Hunt [2] and Dinwoodie [3]. Nevertheless, an establishment of a plain mathematical model and/or definition of numerical parameters for prediction of final deformation of timber beams correctly remain unproved generally.

The serviceability limit state of timber structures is seriously influenced by the increase of deformation due to creep of material. The creep process leads to a time-dependent increase of deformation of structural elements that can cause inadmissible deformations and even collapse of an entire construction. A lot of different rheological models have been designed by various researchers (Burger body [4], models according to Torrati [5], Hanhijärvi [6], Mårtensson [7], Dubois *et al.* [8], Chassagne *et al.* [9], Dinwoodie *et al.* [12], Pierce *et al.* [13]) during the last decades with the aim of describing and simulating the time-dependent behaviour of a natural viscoelastic material – wood. However, the mathematical models derived contain a great variety of constants to be determined by large sample tests.

The aim of this study is to make a contribution to the investigation of relationships for the description of creep of timber beams under natural environmental conditions, to examine known mathematical models and to develop a creep model corresponding to the microclimate of the Baltic States region. The creep model examined in this study has been developed on the basis of the Burger body composed of Kelvin Voigt cells correspondingly to loading cycles. The experimental deformation values from a long-term test are compared with the modelled values obtained using the proposed mathematical model.

2 Background

Mathematical expressions fitted to experimental data are for limited field of use since they are valid for specific conditions of test. In order to overcome this problem some known phenomenological models [4] have been chosen as worthwhile for interpretation of creep behaviour of timber beams. That means that a model is analysed which exhibits the phenomena (deformation in this case) equivalent to those of a real system (timber beam) not taking into consideration the fact that the structure differences are essential. Simple models using combinations of springs and dashpots, which may be represented by a piston in a cylinder containing a viscous fluid, do not correspond directly to discrete molecular structures of real materials, but they do give an understanding of how real materials may respond to stress/strain variations during their life time. In general, the more complex the model the better it will fit the experimental results, but the number of constants are required to be defined on the basis of a great body of experimental data.

A creep model that was developed to predict the effects of load and environment, as well as mechano-sorptive effects on primary and secondary creep behaviour, is composed based on the Burger body concept [4]. Springs and dashpots are used to simulate the elastic and viscous components of the stress/strain response. The springs work like a mechanical analogue of the elastic component. Dashpots simulate the viscous or flow component. The Burger body (Figure 1) combines the Maxwell body and the Kelvin body. The Maxwell body represents the elastic and viscous behaviour of wood producing the total deformation as the sum of displacements of the spring and dashpot joined in series. The Kelvin body consists of a parallel arrangement of a spring and a dashpot representing the total deformation produced by various forces on the spring and on the dashpot. A combination of both models enables the development of mathematical equations for a description of creep behaviour including all the factors and features of the wood involved.

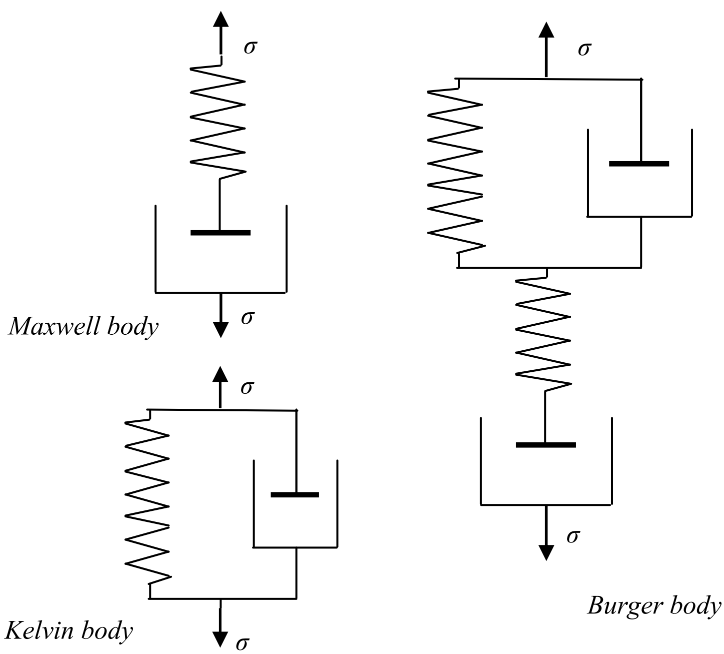

Figure 1: Phenomenological models of creep.

Based on the experimental results, the values of the model parameters were optimized to achieve the best possible compliance between the designed creep model and experimental results of the test.

Considering that the total displacement of the Burger body is the sum of the displacements of the Maxwell and Kelvin bodies, the total strain that is expected to take place in the outermost fibers of a timber beam under a constant bending stress level during time t is expressed by eqn (1) in terms of elastic constant, viscosity modulus, bending stress value and affected by proportion of strength limit used:

$$\varepsilon_t = \sigma\left[\frac{1}{k_w K_e} + \frac{1-exp\left(-t/m\right)}{K_{dp}} + \frac{\sigma}{K_{de}} \times \frac{\sigma}{f_k} \times \sum_{j=1}^{n}\left[1-exp\left(-\frac{\tau}{\eta}\right)\right]\right], \qquad (1)$$

where

ε_t – a total strain at outermost fibers of beam after time t (in hours);

σ – bending stress. Using the presented model two (or more) different loading cycles may be considered – lightweight simulating low season ($\sigma = \sigma_l$) and hard loading for high season ($\sigma = \sigma_h$);

f_k – characteristic bending strength of wood;

K_e – elasticity constant;

k_w – parameter associated with moisture content of wood;

K_{dp} – dashpot modulus regarding the viscous behaviour of wood;

K_{dc} – dashpot modulus associated with accumulation of plastic deformation during previous loading cycles;

m and η – constants;

τ – duration of load cycle in hours;

j – serial number of loading cycle;

n – number of loading cycles;

$n = n_l$ for lightweight loading series and $n = n_h$ for hard load series.

3 Materials and methods

Seventeen timber beams of various span lengths were held under load in four-point bending for almost two years – 612 days. Three groups of timber beams were used for experimental research. Timber beams of group “KS-4” consisted of four specimens having a span length L=1500 mm. Beam group “KS-3” (L=1320 mm) consisted of eight specimens, and group “KS-2” included five specimens. The beams made of Scandinavian Pine (Pinus Sylvestris L.) were simply supported and loaded with two symmetrical forces to produce a constant bending moment in the middle part of beams. The long-term test model is illustrated in Fig. 2. Two series of timber beams – KS-4 (span-depth ratio $L/h \approx 26$) and KS-3 ($L/h \approx 22$) were tested for 612 days, therefore, group KS-2 ($L/h \approx 20$) of timber beams was loaded for 227 days. This group of beams was installed on the 385th day of the test – exactly on 31st December, 2012. To achieve real service conditions, the experimental test was carried out in an unheated building with uncontrolled climate conditions. The building is located in Latvia, approximately 60 kilometres from the Baltic Sea.

The forces attached represent the percentages of variable load from the total bearing capacity of a beam converted to design fiber stress in accordance with condition u_{fin}=L/150, where u_{fin} is the final deflection declared by Eurocode 5:

$$u_{fin} = u_{inst,g} \times \left(1 + k_{def}\right) + u_{inst,q} \times \left(1 + \psi_2 \times k_{def}\right), \tag{2}$$

where $u_{inst,g}$ and $u_{inst,q}$ are instantaneous (elastic) deflection values produced by permanent and variable load, k_{def} is the deformation (creep) factor for permanent loading (k_{def} = 2) and ψ_2 is the reduction factor for variable load to its quasi-permanent value (ψ_2=0.5) and L is the span of test beams.

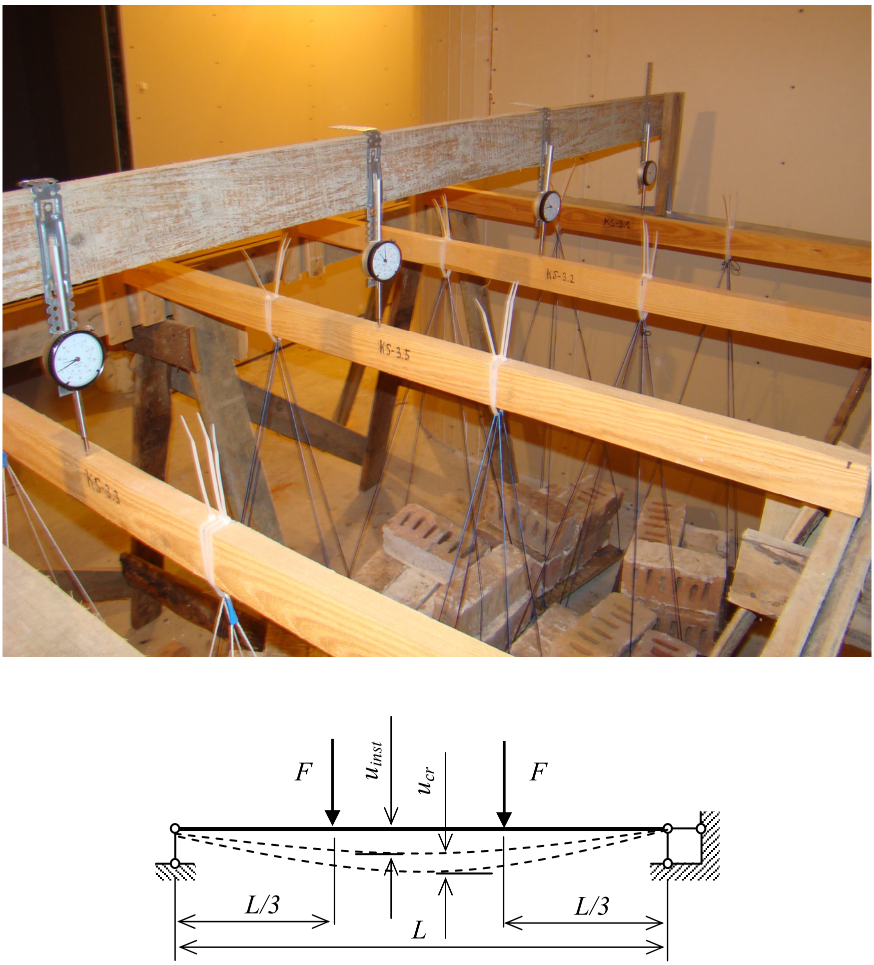

Figure 2: Long-term bending test setup and static model.

The timber beams were manually loaded with weights. Dial test indicators for monitoring of deflection were fixed on a rigid frame and their arms moved out to

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the compressed side of the timber beams. The loading regime was set to simulate the service conditions of roof structures for almost the entire two year test period. A full load was attached for the winter season (65 days) and 50 per cent load was attached for the remaining period of 562 days which includes the simulation of a realistic non-snow winter season in Latvia. Deflections in the middle of the span were measured after applying a full load (initial) and daily during the test. The moisture content of wood was measured using Wood Moisture Meter MD-2G. The temperatures and air humidity both inside and outside the room were fixed using hygrothermometer Testo 605-H1.

4 Analysis of results

4.1 Application of bending theory

Experimentally, the midspan deflection of beams was measured to the upper compressed surface. In order to transfer from this deflection (u_t) to the corresponding strain values of the outermost fibers, the geometrical relationships set/stated for the deformed shape of a top side axis as a segment of the circle has been treated (see Fig. 3(a)). By using geometrical relationships the radius of curvature (ρ) may be expressed through span and centre angle of curvature.

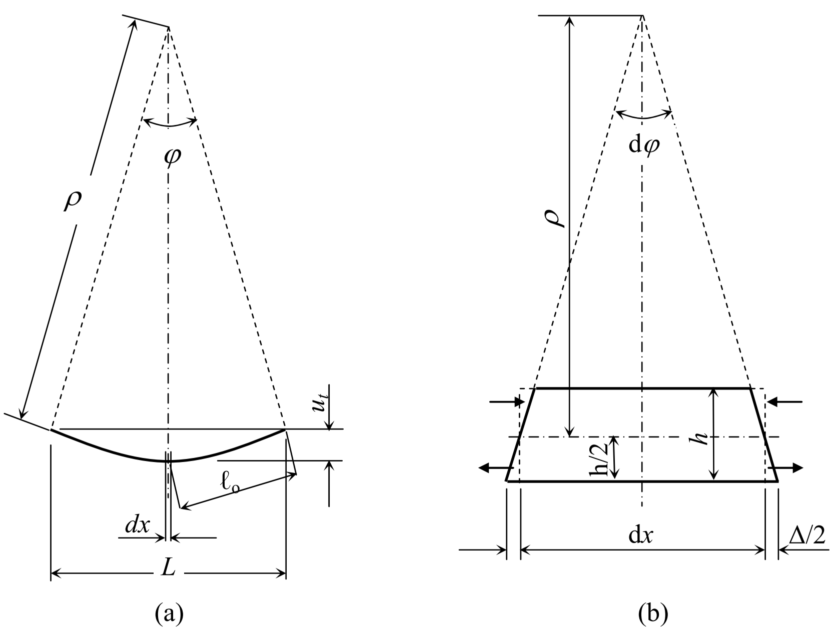

Figure 3: Geometric illustration of bending shape.

The strain value at the outermost fibre may be expressed using geometrical relationships of an isolated segment (dx) taken from the beam deformed elastically and applying with the simplification for straight sides (see Fig. 3(b)).

Taking into consideration both Hooke's law and geometrical relationships we get the strain equation as follows:

$$\varepsilon_{el} = \frac{h}{2 \times L \Big/ \left(2 \times \sin\left(\frac{\varphi}{2}\right) + \frac{h}{2} \right)} \tag{3}$$

4.2 Creep curves

Using experimental data, the relative creep (known also as the creep coefficient) was quantified and expressed as a percentage of the instantaneous elastic deflection (u_0): $u_0 = 100 \times (u_t - u_0)/u_0$, where u_t is the deflection at time t.

When examining the average creep curves of all timber beam groups (Fig. 4), a great difference in values of relative creep were observed, though only the highest quality specimens without knots or other defects were selected out from the sawmill. The average relative creep value for timber beam group KS-4 is 12%, for group KS-3 it is 37% and up to 97% for group KS-2.

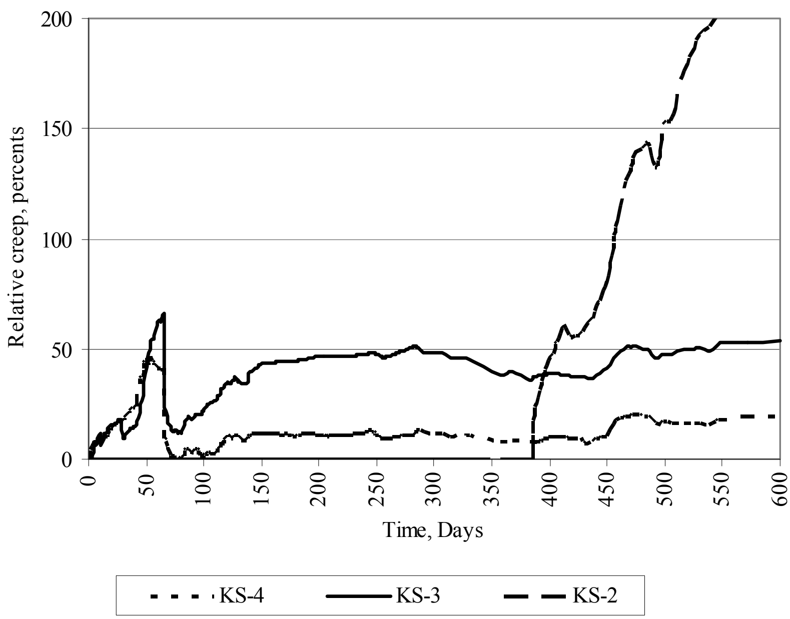

Figure 4: Relative creep curves.

It has been found that the average relative creep value for the timber beam group KS-2 (Fig. 7) reached 97% regarding the entire test period while the average relative creep value during 227 days of the test period for single specimen reached even 230%. While inspecting the behaviour of the specimens of group KS-2, even higher values of relative creep were registered. The rise of the average relative creep curve was slightly gradual. Variations of creep behaviour between timber beams of group KS-2 indicate a considerable influence of mechanical and physical properties, such as width of annual rings, percentage of latewood, slope of grain and the plane of the cut (radial or tangential) as well. Average relative creep curves of beam groups KS-3 and KS-4 are illustrated in Figs 5 and 6. This is the aspect that needs to be studied in future research to enable a more accurate explanation of these variations of relative creep observed regarding an individual beam group.

The strain curves of all the tested timber beam groups represent the mechano-sorptive (MS) part of creep that demonstrates a negative impact of a changing microclimate to load-bearing constructions under natural environmental conditions. The increase of creep during fluctuations of moisture is faster than is observed at a relatively constant moisture content.

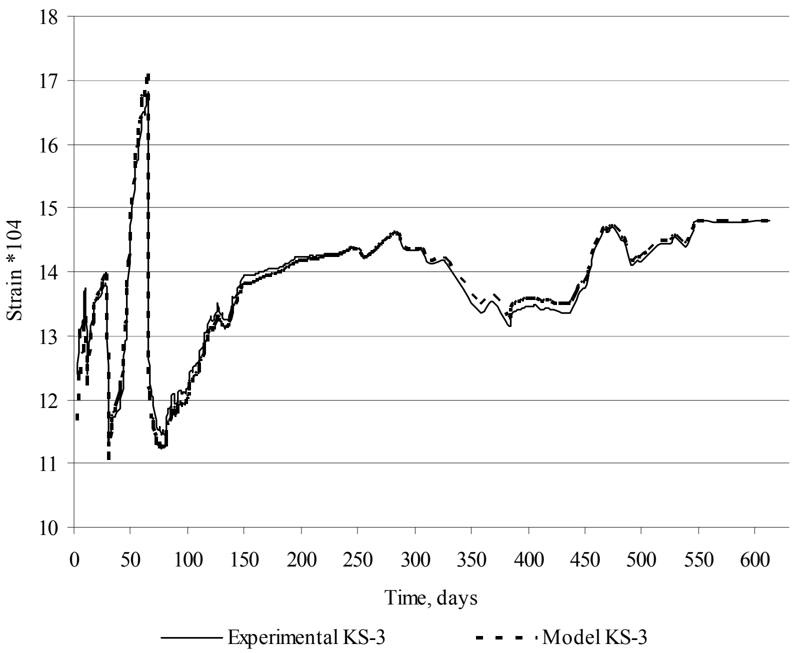

Figure 5: Development of deformations for KS-3.

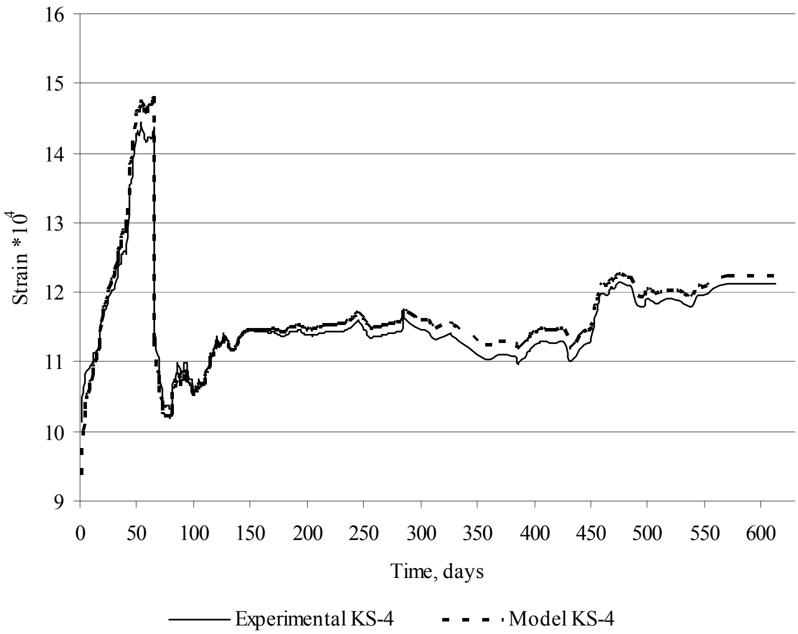

Figure 6: Development of deformations for KS-4.

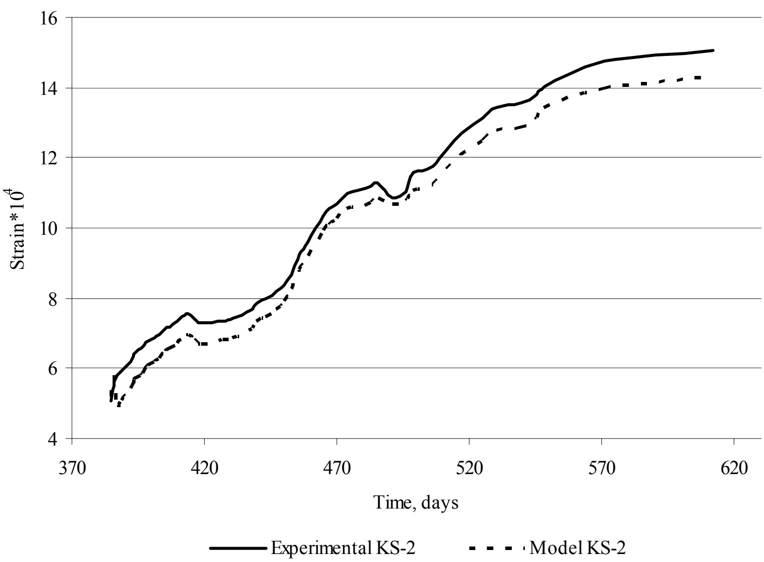

Figure 7: Development of deformations for KS-2.

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4.3 Discussion

When examining the conformity of creep behaviour between the obtained experimental data and modelled curves, some discrepancy was observed. The biggest difference between both curves was displayed corresponding to the period of fluctuating temperature, relative humidity and moisture content.

During a relatively stable time span of climatic parameters, the modelled creep curve corresponded to the curve of the experimental data almost perfectly.

Each cycle of moisture content changes initiated an increase of deformation. The raise of deformation was observed both at the time of dehumidification, and during humidification. The amplitude of strain alterations during the decrease of moisture content of wood was much bigger than it was during humidification of the specimen.

It was observed from a long-term test that the fluctuations of relative humidity of air, moisture content of wood and temperature accelerated creep behaviour according to which the increase of deformation was observed. The increment of deformation was greater during dehumidification than at the time of humidification. Timber beams exhibited mechano-sorptive creep in those periods where it was illustrative that mechano-sorptive creep does not occur during steady-state moisture conditions. It is very important to predict and consider this mechano-sorptive process because it may result in great deformation or even early failure of a construction.

5 Conclusions

This paper represents the first results of extensive research that is aimed at contributing to the methodology of prediction of final deflection of timber beams after life time years and to establish an adequate and practically applicable mathematical model.

It has been proved by tests that a higher rate of mechano-sorptive creep corresponds to the dehumidification period comparing with the one during humidification. The development of mechano-sorptive creep lies low during steady-state moisture conditions.

This study proved that the mathematical model devised/developed can be used for the prediction of long-term behaviour of timber beams in bending. During steady relative humidity, temperature and moisture content of timber beams, mathematical model simulates creep behaviour accurately enough, but under variable climatic conditions, the behaviour of the test samples was simulated with some discrepancy. The faster the fluctuation, the greater the differences between the experimental and model curves.

Future study is needed in order to examine how creep behaviour is influenced by mechanical and physical properties of wood and its structure per se.

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