Experimental investigation of behaviour of timber beams under natural environmental conditions

Aivars Brokans  
Doctoral student  
Department of Structural Engineering  
Latvia University of Agriculture  
Latvia  
brokans.aivars@inbox.lv

Lilita Ozola  
Associate Professor  
Department of Structural Engineering  
Latvia University of Agriculture, Latvia  
Lilita.Ozola@llu.lv; lit1oak@llu.lv

Summary

The current work is devoted to the investigation of relationships in creep of timber beams under natural (uncontrolled) environmental conditions and is aimed to define an appropriate mathematical model for the prediction of final deformation after some loading cycles. The presented creep model is a new version of the known Burger body concept. The proposed model has been numerically tested by estimates obtained from four-point bending tests in static loading of pine (Pinus Sylvestris) beams. There are two different loading regimes applied in testing: full load for 65 days (winter season) and half load for spring and summer seasons (220 days). It has been verified that the proposed model fits well with experimental results and may be used as appropriate for bending strain prediction in timber beams under natural environmental conditions with possible improvements in the future.

Keywords: Timber Beams, Bending, Duration of Load (DOL) effects, Creep

1. Introduction

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 the prediction of final deformation of timber beams correctly remain generally unproved. The prognosis of long-term behaviour of timber structures under service loads and environmental effects is one of the most discussed issues in research and design of timber structures, as deformations develop due to very complicated physical mechanical time-dependent effects influenced by a wide range of factors such as variable moisture and temperature, stress level, particular structure of wood and others that should be taken into consideration to predict deformations of timber structures more accurately for design purposes. Serviceability limit state of timber structures is seriously influenced by the increase of deformation due to creep of the material. During the last decades many rheological models have been developed by researchers (Burger body [4], models according to Torrati [5], Hanhijärvi [6], Mårtensson [7], Dubois et al. [8], Chassagne [9]) with the purpose to describe the time-dependent behaviour of wood. The creep model examined in this study has been developed basing on the known Burger body [4] composed by n Kelvin Voigt cells corresponding to loading cycles. The experimental deformation values are compared with the ones derived using the proposed mathematical model.

The aim of this study is to make some contribution to the investigation of relationships for the description of creep of timber beams under natural environmental conditions, to examine some a mathematical model and to define a range of parameters introduced in the prognosis of the final deformation under variable loads.
2. Background

As this study is aimed at the prediction of total deformation in bending under normal service stresses ranging no more than 50% of the ultimate stress limit, it is assumed that timber behaves as a linear viscoelastic material. Thereby the Boltzmann’s principle of superposition has been applied to predict the deformation after some loading cycles [3]. Creep behaviour of timber has been interpreted with the aid of a mechanical model comprised of a combination of springs (elastic component) and dashpots (to simulate the viscous component). Simple models using combinations of springs and dashpots do not correspond directly to the discrete molecular structures of materials, but they do aid in understanding how the materials will respond to stress/strain variations.

A mathematical model developed for the prediction of total deformation due to the effects of cyclic load and variable environmental conditions is composed basing on the Burger body mechanics [4]. The four-element Burger body represents the principal features of the time-dependent behaviour of wood as a natural composite using a combination of a Maxwell body consisting of a spring and a dashpot joined in series and a Kelvin body consisting of a parallel arrangement of the spring and dashpot elements (see Fig. 1). The displacement \( u_B \) of the Burger body after time \( t \) due to the action of force factor \( P_o \) has been expressed as the sum of the displacement of the Maxwell and Kelvin bodies [4] and given by the equation:

\[
 u_B = P_o \left[ \frac{1}{k_e} + \frac{1}{k_{de}} \left( 1 - e^{-t/r_v} \right) + \frac{1}{r_v} t \right].
\]  

(1)

The Maxwell body alone describes the elastic and viscous behaviour (constants \( k_e \) and \( r_v \)), and the Kelvin body represents the delayed elastic response (parameters \( k_{de} \) and \( \tau \)).

Aspiring to develop the expression for the final deformation sufficiently adequate in results and not complicated in use the total strain \( \varepsilon_t \) expected to take place in the side fibers of timber beams expressed in terms of elastic constant, viscosity constants, bending stress value and affected by the proportion of strength limit used is presented in the format as follows:

\[
 \varepsilon_t = \varepsilon_e + \varepsilon_v + \varepsilon_c = \frac{\sigma}{K_e} \left[ \frac{1}{k_w} + \frac{1}{k_{dp}} \right] + \frac{\sigma}{K_{dp}} \times \sum_{j=1}^{n} \left[ 1 - \exp \left( -\frac{\tau}{\eta} \right) \right]
\]  

(2)

where:

- \( \varepsilon_t \) – total strain at outermost fibres of beam after time \( t \) (in hours);
- \( \varepsilon_e \) – elastic component of strain;
- \( \varepsilon_v \) – strain component due to viscoelastic behaviour of material;
- \( \varepsilon_c \) – additional creep strain component associated with accumulation of deformation during previous loading cycles;
- \( \sigma \) – 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 describing the viscous behaviour;
- \( K_{de} \) – dashpot modulus describing the loading history;
- \( m \) and \( \eta \) – constants;
- \( \tau \) – 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

Twelve timber beams were tested under a long-term load in a four-point bending testing rig. The beams of pine (Pinus Sylvestris) were simply supported and loaded with two symmetrical forces to produce a constant bending moment in the middle part of the beams. The long-term test model is illustrated in Fig. 2. To simulate the real service conditions the tests were carried out in an unheated building with an uncontrolled microclimate. The building is located in Latvia, approximately 60 kilometers from the Baltic Sea.

The maximal forces attached represent the load value corresponding to the total bearing capacity of a beam in accordance with the serviceability limit state condition \( u_{\text{fin}} = L/150 \), where \( u_{\text{fin}} \) is the prognosis of final deflection declared by Eurocode 5 (see Fig. 2 right for illustration of deflection components):

\[
u_{\text{fin}} = u_{\text{inst}} + u_{\text{cr}} = u_{\text{inst},g} (1 + k_{\text{def}}) + u_{\text{inst},q} (1 + \psi_2 k_{\text{def}}),
\]

where \( u_{\text{inst},g}, \ u_{\text{inst},q} \) — instantaneous (elastic) deflection values produced by permanent and variable load correspondingly,
\( k_{\text{def}} \) — deformation (creep) factor for permanent loading \( (k_{\text{def}} = 2) \),
\( \psi_2 \) — reduction factor for variable load to it’s quasi-permanent value \( (\psi_2 = 0.5) \).

The timber beams were manually loaded with weights. Dial indicators for deflection monitoring of timber beams were fixed on a rigid frame and placed on the compressed side of the beams. The loading regime was created so as to simulate the service conditions of roof structures: full load acts for the winter season (about 65 days) and 50 percent attached for the rest period (no snow) of 220 days. Deflections in the middle of the span were measured after applying a full load (initial) and daily during the test. Moisture content of the wood was measured using a Wood Moisture Meter MD-2G. The temperature and air humidity both outside and inside of the room were fixed using a hygrothermometer Testo 605-H1.

Using experimental data the relative creep (known also as the creep coefficient) was quantified expressed as a percentage of the instantaneous elastic deflection \( (u_i) \): \( \epsilon = 100 \times (u_t - u_0)/u_0 \), where \( u_t \) is the deflection at time \( t \). In order to transfer from the midspan deflection \( (u_t) \) measured to strain of the outermost fibres the geometrical relationships in bending has been used. See Fig. 3 left. The radius of curvature \( (\rho) \) is expressed through the span and centre angle of curvature. The strain \( (\epsilon_{el}) \) at the outermost fibre may be expressed by using Hooke’s law and geometrical relationships in elastically deformed beam segment with simplification for straight sides (see Fig. 3 right):

\[
\frac{\epsilon_{el}}{dx} = \frac{A}{2L/[2\sin(\phi/2)+h/2]} \approx \frac{2h \times \sin[\arctg(2u_t/L)]}{L}. 
\]
4. Results and discussion

In winter season (65 days) when a full load was attached to the beams the average air temperatures (TC) inside the building were +0.3 °C (±0.5 °C) with a range of variation of 15 °C and at the same period the outside average was -2.4 °C with a range of variation 24.1 °C. The average air temperatures for the rest period of testing while the beams were sustained under a decreased load, were 14.8 °C (outside) and 17.7 °C (inside) with a range of variation 24.7 °C and 30.8 °C.

In winter season the relative humidity (RH) of air inside the building varied between 48.6% and 81.7%, average 68.6% (±3%). The measured RH values for spring and summer time varied between 59% and 75.6%, average 67.5%.

During the testing the average moisture content (MC) of all timber beams decreased from 27.6% on the first day of the test down to 9.8% on the 285th day. The average value of moisture content during the winter period was 20.5% and 11.6% for spring and summer time.

Relationships between relative humidity (RH), temperature (T) and relative deflection are shown in Fig. 4. In order to improve the readability of graphs the relative deflection displayed represents $u/L$ value multiplied by $10^4$.

Average relative creep (expressed in percentage) curve versus time calculated from all twelve timber beams is shown in Fig. 5. Average relative creep value for winter season was 24.3%, whereas for spring and summer period - 28.9%.

It is considered that the relative creep curve displayed in Fig. 5 represents viscoelastic, mechano-sorptive (MS), pseudo-creep and recovery as well. This is a complex phenomenon that has been extensively studied for half a century without reaching full understanding. The creep rate of timber is accelerated to a greater extent due to moisture variations, i.e. the timber exhibit mechano-sorptive creep. This process is very demonstrative in Fig.5 observed between the 30th and the 145th day of testing. Timber beams were partly unloaded at the 65th day of test taking off 50% of the full load responding to the end of winter season. Despite substantial reduction of full load, relative creep continued to increase up to the 145th day of testing. On this day there was a margin where amplitude of RH and T fluctuations became much slighter.
The Burger model has been successfully used for predicting creep behaviour of wood [4], [10], [11]. Note that all applications have been carried out under constant or controlled climatic conditions. Because of this aspect, a modified creep model proposed in this study represents a reasonably accurate agreement with the experimental data. Based on the experimental results, the constants of the model parameters were optimized to achieve the best compliance. In Fig. 6 the strain curves produced using measured deflection values and the modelled one using Equation 2 are displayed.

It is found by examining experimental and model data for every beam tested that for some individual beams some discrepancy between strain values resulting from the mathematical model proposed and experimental data processed emerges. This difference can be explained by the fact that properties of timber beams differ in some degree, variation of moisture content of timber beams were significant for first forty days of testing while equilibrium moisture content was reached, and in addition density in the same way as width of the annual rings and amount of latewood...
varied too. Note that the compliance between model and experimental average values fits well.

It is proved that the Burger body model has been successfully used for the description of the creep behaviour under constant load and controlled temperature-humidity conditions. Natural environmental conditions involve some additional uncertainty due to the unforeseen mixing of affecting factors yet in a limited range. Discrepancy between experimental and model curve emerges in the time period from the 30th day to the 150th day of testing, directly during the period when climatic parameters (RH and T) present the marked variation. Average curve of experimental data and modelled curve in hours (see Fig. 7.) are reproduced to give the conception of deviation between average curves on a larger scale.

Creep deformations in timber structures depend on the season – variations in moisture causes fluctuations in creep curves. Relative humidity fluctuations and radical decrease of air temperature (indoor temperature decreased to minus 10º C on the 40th day of testing), accelerated creep rate that continued even when a constant increase of air temperature was observed. The creep development process in a period of fluctuating temperature and relative humidity (in winter) is much faster than it is in a more persistent temperature and humidity regime (in spring, summer). Small cross-section beams are influenced by humidity cycling more than large sections.

Fig. 6 Experimental and model curves
In order to examine the Eurocode conditions the numerical testing of Equation 3 was performed inserting the measured elastic deflection \( u_{\text{inst},t} \) and the final deformation values \( u_{\text{fin},t} \) detected in the process. Speculating for examination of combination factor \( \psi_2 \) recommended by Eurocode the factor \( C_t \) was worked out:

\[
C_t = \frac{u_{\text{fin},t} - u_{\text{inst}}}{k_{\text{def}} \times u_{\text{inst}}},
\]

(5)

It is clear for test conditions described above that the deformation factor may be assessed as corresponding to 3rd service class value \( (k_{\text{def}} = 2) \). The value of \( C_t \) factor detected by numerical trials may be assumed as representative of the quasi-permanent part of variable load producing the creep.

The average values of characteristics of beams in test series are presented in Table 1, where symbols are used as follows: \( \sigma \) - the bending strength calculated under assumption of elastic behaviour of material, \( L \) - span of beam, \( h \) - depth of section, \( E_{\text{test}} \) - modulus of elasticity found from elastic deflection equation in four-point bending, \( MC \) - moisture content of wood, \( \Delta c_r \) - average increment of relative creep, generated daily.

**Table 1 Average Characteristics of Test Beam Series**

<table>
<thead>
<tr>
<th>Mark</th>
<th>( \sigma ), MPa</th>
<th>( L/h )</th>
<th>( L/\text{u}_{\text{inst},t} )</th>
<th>( L/\text{u}_{\text{fin},t} )</th>
<th>( E_{\text{test}} ), MPa</th>
<th>( MC ), %</th>
<th>( \Delta c_r ), %</th>
<th>Prediction ( C_t )</th>
</tr>
</thead>
<tbody>
<tr>
<td>TB-1…</td>
<td>5.6</td>
<td>40</td>
<td>200</td>
<td>105</td>
<td>11000</td>
<td>18.5</td>
<td>1.0</td>
<td>0.4</td>
</tr>
<tr>
<td>TB-2…</td>
<td>9.0</td>
<td>22</td>
<td>180</td>
<td>120</td>
<td>10100</td>
<td>22.0</td>
<td>1.0</td>
<td>0.5</td>
</tr>
<tr>
<td>TB-3…</td>
<td>9.7</td>
<td>22</td>
<td>210</td>
<td>130</td>
<td>9900</td>
<td>21.0</td>
<td>1.1</td>
<td>0.5</td>
</tr>
</tbody>
</table>

Notice that also the different standard models built-in the MS Excel were examined to describe the relative creep deflection \( (u_c) \) relationship versus time \( (t) \) according to the test data [12]. For all that the best fitting between test curve and regression model may be obtained by exponential, logarithmic and polynomial curves, in this study the linear relationships (Equation 6) were found as sufficiently good approximators testified by the coefficient of determination values close to unity.

\[
u_{c,t} = a + b \times t.
\]

(6)
5. Conclusions

This study provides background for future research trends with the purpose to establish a mathematical model suitable for the predictions of final deflection of timber beams after determinate number of loading cycles.

It is presumed by results of this study that the proposed mathematical model works well when fluctuations of relative humidity and temperature of air are negligible, and moisture content of wood remains constant while for higher ranges of humidity and temperature the strain values obtained on experimental basis and modelled ones differ in greater extent. A future research is needed for evaluation reliably in whatever degree any of model parameter represents the contribution to final deformation. Also more test beams and larger data samples are needed to prove plausible the proposed model.

Changes of relative humidity, temperature and subsequent variation of the moisture content of wood accelerated creep behaviour with following increment of deflection. It is illustrative that mechano-sorptive creep does not occur during steady-state moisture conditions.

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7. References