Estimation of Stress Distribution in Timber Beams under Steady Changes of Moisture Content

Arkadiusz Lesko

1 Warsaw University of Technology, Faculty of Civil Engineering, Division of Wood Structures, Al. Armii Ludowej 16, Warsaw 00-637, Poland

a.lesko@il.pw.edu.pl

Abstract. The paper relates to the effect of steady-state change of moisture content in timber elements. Several constitutive models of the material used in the literature have been presented. For the purpose of the simulation, a three-dimensional FEM model was prepared. Results were presented based on four models of moisture distribution and three sets of material parameters. Based on the literature and simulation results, the necessity of changing the practical design approach was discussed.

1. Introduction

Timber structures (both classic and modern ones) are exposed to adverse effects related to the fickleness of the surrounding environment. In addition to biological and chemical hazards, an impact of the variability of environmental physical parameters in the form of relative humidity and air temperature is important. These parameters affect the physical and mechanical properties of timber, which leads to the formation of additional internal reactions (in the form of stresses). Design standards (such as [1]) consider the influence of humidity on a timber element by defining service classes that depend on the average humidity content in an annual cycle. The service class influences, inter alia, the reduction of the strength parameters of wood (in relation to the characteristic values). However, a very important issue is a "sudden", non-averaged change in humidity, which causes a significant increase in internal forces.

A change in the humidity of the environment causes a change in humidity of the timber element until the equivalent humidity is reached on the contact surfaces with the surroundings [2]. The diffusion of moisture in the element is not constant and does not reach the linear state in the entire volume of the element. For this reason, wooden elements in various volume zones are subject to compression and tension. These conditions often lead to failure (due to delamination) of beam elements or at best to unaesthetic cracks that weaken the structure. Numerous examples have been described in the literature [3] which show that the load-bearing capacity of timber elements is strongly dependent on their seasoning. The increasing usage of timber (in the form of LVL, for example) in objects highly exposed to changing external conditions (e.g. bridges) introduces the need for a deeper understanding of the problem and requires a new design approach.

As the most important aspect affecting the scale of negative effects resulting from changes in moisture of the timber is recognized as a percentage size of humidity change [4], the way of its...
distribution in the cross-section and the scale of free shrinkage/swelling. The influence of time (rheological phenomena) or cyclic moisture load (hysteresis phenomenon) does not significantly affect the obtained results (increase in loads from changes of damp) [5].

2. Moisture penetration in timber

The flux of moisture in the timber element may be defined by using the Fick's second law:

\[
\frac{\partial u}{\partial \tau} = D \frac{\partial^2 u}{\partial x^2}
\]  

(1)

Analytical solutions [6] and numerical solutions [7] have been proposed in the literature but the analytical solution has some drawbacks. It is necessary to maintain a constant diffusion coefficient which is not consistent with the actual behavior of the material. In addition, it should be noted that equation (1) is correct for the wetting of the element (moisture increase in wood) [8]. In the literature [9], corrections to equation (1) have been proposed in order to be able to reproduce processes taking into account drying or cyclic changes of humidity.

Through mathematical analogy, it is possible to calculate the flow of moisture in the timber structural element with the use of a temperature flux module [10]. The problem of coupling the deformation state and imitating the humidity, temperature state is solved then. [11]. However, it is possible to simplify further the form of imposing a temperature (implicitly humidity) field by applying a previously determined field on a specific zone of the simulated element [12]. This simplification accelerates the simulation but does not allow to observe non-linear effects that could be taken into consideration by the use of an appropriate constitutive model (for instance (3)).

![Figure 1. Average moisture content in LVL beam 90 x 100 x 600 [mm] in seaside town of Asa (Sweden) [14]](image)
literature are carried out taking into account severe operating conditions (eg. bridge elements in the environment with high variability of relative humidity). In a typical structure made from glued laminated timber, the changeability of wood moisture is avoided by bringing the element to an equivalent humidity level, corresponding to the most common conditions occurring in the embedded place and by protecting the element against moisture sorption from the air (by coatings). According to above and basing on practical experience, discussions and estimations presented in this publication are based on four distribution curves of the humidity distribution (Figure 4) where the maximum difference in moisture level is 3%.

3. Timber constitutive models

The macroscopic characteristics of wood are influenced by circle shaped regions with an annual increase, which is directly related to the way of natural tree growth. The material response to the external load must correspond to this characteristic, therefore it is necessary to use an orthotropic material model with a cylindrical coordinate system (Figure 2A). The naturally occurring phenomenon is also the fragmentation of the wood structure in the radial direction to the sapwood and the heartwood (Figure 2B). Sapwood performs the function of the water and mineral salts transport, heartwood partially loses some transport capacity in favor of stiffness growth - it is a frame or a core of a growing tree. This partition clearly implies that the material parameters change in the radial direction also, but this fact is not well known and described (in particular with regard to the material parameters). The constitutive models quoted below do not take into account this phenomenon and are based on the assumption of additivity of individual deformation values.

\[ \{ \varepsilon \} = \{ \varepsilon^e \} + \{ \varepsilon^{cr} \} + \{ \varepsilon^{el} \} + \{ \varepsilon^{ms} \}, \]  

(2)

3.1. Constitutive model I

In publication [12] a material model consisting of 4 components was proposed where the complete deformation vector contains additive deformations: linear elastic strain from external loads \( \varepsilon^e \), viscoelastic creep \( \varepsilon^{cr} \), elastic moisture expansion \( \varepsilon^{el} \) and mechano-sorptive strain \( \varepsilon^{ms} \). The authors of the publication agnize that the part responsible for creep is so small that it can be considered negligible. Partly reversible deformations from mechano-sorption strain were considered irreversible also. The brackets \{ \} indicate the vector.
3.2. Constitutive model II
In the publication [11] constitutive model above (2) was developed with additional components taking into account the influence of time on the behavior of the material. The complete deformation vector contains an additive deformation: linear elastic strain from external loads $\varepsilon^e$, elastic moisture expansion $\varepsilon^m$, viscoelastic creep $\varepsilon^{ve}$, and mechano-sorption strain composed of the reversible $\varepsilon^{ms}$ and irreversible $\varepsilon^{ms,irr}$ part.

$$\{\varepsilon\} = \{\varepsilon^e\} + \{\varepsilon^u\} + \{\varepsilon^{ve}\} + \{\varepsilon^{ms}\} + \{\varepsilon^{ms,irr}\}, \quad (3)$$

The constitutive models proposed above take into account a number of phenomena, and in each of them, it is necessary to use a number of parameters depending on many factors affecting the lumber (such as age, quality, type, a region of growth, seasoning time, etc.). In the papers [11,12,17] a significant influence on the results of deformations from elastic expansion/shrinkage was indicated - according to [17] this phenomena is dominant (strain values are several times higher than from the remaining effects). Therefore, a simplified model (4) consisting of linear elastic strain from external loads $\varepsilon^e$ and deformation due the elastic expansion / shrinkage $\varepsilon^u$ was adopted for the calculations presented below.

$$\{\varepsilon\} = \{\varepsilon^e\} + \{\varepsilon^u\}, \quad (4)$$

4. Finite element modeling

4.1. Aim of the simulation
The aim of the simulation is to estimate the influence of different moisture distribution models and the influence of changes in humidity parameters adopted in accordance with the literature [11,18,19] on the distribution of stresses in the beam element. It should be noted that the element was simulated in the steady-state condition (without moisture flux simulation).

4.2. Geometric assumptions
The spatial model was created as a beam element with 160x160x1000 [mm] dimensions, where the displacement was assumed to be $U(R,T,Z) = 0$ (Figure 3) at the end surfaces. The model was built from solids connected by a "TIE" module [10] where on each element a cylindrical coordinate system located in the same place was imposed (imitating a real wooden beam cut out from the trunk). Due to the fact that we assume a set of moisture levels as a steady state, the analysis is carried out as a 3D Stress. The mesh consisting of C3D8 finite elements has been selected so that the dimension of a single element does not exceed: 5x5x100 [mm] for outer layers and 10x10x100 [mm] for internal layers (Figure 5B).

![Figure 3. Model with coordinate system and boundary conditions](image)

4.3. Material assumptions
The material was adopted as orthotropic and parameters were assumed in accordance with [12] (the influence of humid change in density and temperature was omitted).
\[ E_i = E_{i,ref} \cdot \left( 1 + c_1 \cdot (u-u_{ref}) \right), \]  
\[ G_{ij} = G_{ij,ref} \cdot \left( 1 + c_1 \cdot (u-u_{ref}) \right), \]  
where:
\[ E_{r,ref} = 600 \text{ [MPa]}, \quad E_{t,ref} = 600 \text{ [MPa]}, \quad E_{z,ref} = 12\,000 \text{ [MPa]}, \]
\[ G_{rt,ref} = 40 \text{ [MPa]}, \quad G_{rz,ref} = 700 \text{ [MPa]}, \quad G_{tz,ref} = 700 \text{ [MPa]}, \]
\[ \nu_{rt} = 0.558, \quad \nu_{rz} = 0.038, \quad \nu_{tz,ref} = 0.015, \]
\[ c_1 = -2.6, \quad u_{ref} = 20\%. \]

Comparative analysis was done based on three sets of humidity expansion parameters proposed in the literature.

Parameter Set I (according to [11]) \[ \alpha_r = 0.13, \quad \alpha_t = 0.27, \quad \alpha_z = 0.005, \]
Parameter Set II (according to [18]) \[ \alpha_r = 0.11, \quad \alpha_t = 0.22, \quad \alpha_z = 0.005, \]
Parameter Set III (according to [19]) \[ \alpha_r = 0.07, \quad \alpha_t = 0.15, \quad \alpha_z = 0.005, \]

4.4. Moisture load

The chart below (Figure 4) shows four models of moisture distribution. As initial humidity 9% level was assumed. This load was implemented using the "Predefined fields" module available in Abaqus. The way of load application and finite element mesh view are presented below (Figure 5).

![Figure 4. Four moisture distribution models](image)

![Figure 5. a) Distribution of moisture load in regard to a model b) Distribution of moisture load in regard to a FEM mesh](image)
5. Numerical modeling – selected results

5.1. The effect of different moisture distribution models application on delamination stresses

Based on the geometrical assumptions and parameters quoted in this paper, the influence of the moisture change distribution on tensile stresses caused by the elastic volume change of the considered beam was checked. The results are presented in relation to the planes (lines) indicated below (Figure 6).

![Figure 6](image)

**Figure 6.** Location of planes/reference lines with respect to which results are presented

The graph below (Figure 7) compares the distribution of tensile stresses across the fibers ("S22") across the element in the plane of symmetry, so as to minimize the effect of boundary conditions (in relation to Line "A" - Figure 6). A distinct change in the character and value of stresses is visible depending on the way of the element loading (moisture change). The maximum values of tension and compression of wood across the fibers exceed the values of bearing capacity from design standards [1], which may be caused by the lack of local cracks in the timber model.

![Figure 7](image)

**Figure 7.** Influence of humidity change distribution on stress distribution caused by elastic expansion - graph relative to "Line A" (Figure 6)

In order to better depict the nature and scale of stress change across the fibers caused by the moisture change, three-dimensional surfaces with a shape corresponding to the stress value were presented (Figure 8). The results below refer to Surface I (Figure 6). The red line indicates the place of "zeroing" of the delamination stress values. Above this mark, the element is in compression - below in
tension. There are differences in the obtained results between the adopted distribution models. It can be estimated that the impact of the support zone reaches a maximum of 15% of the element length - in the rest of the beam results are undisturbed.

**Figure 8.** Influence of humidity change distribution on stress distribution caused by change of element's volume - maps relative to "Surface I" (Figure 6)

Maps presented above can be created at each layer through the height of the beam. Hereby, we will obtain a set of red lines (or more precisely points) which allows us to create a real "tensile zone volume". The volume of such a zone is referred to in the design standard as a simplified calculation of the ridge zone volume for girders with varying geometry [1]. The graphic below represents the tension zone in the considered element assuming that the moisture load is applied in accordance with the model distribution IV. It can be seen that delamination stresses across the fibers occur in the greater part of the element's volume.
5.2. The effect of moisture expansion coefficients change on delamination stresses

Based on geometrical assumptions and parameters quoted in this paper, the influence of various values of moisture expansion coefficients on tensile stresses across caused by the elastic volume change of the considered beam was checked. The results shown below (Figure 10) are presented with respect to Line "A" (Figure 6). For both compression and tension, the change in parameters significantly affects the size of the results obtained (differences in their maxima exceed 100%).

**Figure 9.** Tension zone elements at IV humidity distribution model
A) Points cloud B) A set of approximation surfaces (based on points cloud)

**Figure 10.** Influence of different moisture expansion parameters on delamination stresses in relation to Line "A" (Figure 6)
6. Conclusions

Delamination stress caused by the change of moisture content in timber structures is a very important issue that is often overlooked at the design stage. While the change in material parameters or the increase of the loads by applying the appropriate standard factors [1] significantly limits the stresses in the structure, this approach does not consider additional stresses coming from instantaneous humid changes. It should be considered whether the simplified design approach does not limit excessively considerations regarding the influence of moisture change on the load-bearing capacity of structural components both on a global and local scale.

In the study simplified model of the material was used which takes into account the wood expansion/shrinkage phenomenon. FEM simulation has shown that the stress that is caused by the change of moisture content is very important in the context of the material strength and the load-bearing capacity of the structure. Additionally, the type of the adopted load distribution and the adopted material parameters have a very large impact on the results.

In the literature [20], it was proposed to divide the section of the beam element into two zones: active and passive, which was confirmed by the simulation presented in the paper (Figure 11). This partition is based on the determination of the compression and tension zones for which it would be possible to introduce additional conditions or restrictions in the design standards. The results of the simulation showed that the zones dimensions do not only depend on the cross-section proportions and the moisture change of the element (as postulated in [20]) but also on the humidity distribution way (implicitly the intensity of the moisture flux and material parameters - e.g. diffusion coefficients (1)). Introducing an active and passive zone division into to design standards requires further research but it is a good step to reduce the risk of structural failures.

![Figure 11. A) Active and passive zone depends on proportions of element's cross-section [20] B) Results of simulation - active and passive zone (in the vertical direction).](image)

In addition to the heavy operating conditions of the buildings where LVL is applied, the imposed constraints (in the form of junctions of the sub-structural elements) additionally cramp the structure, which limits their unhampered work. Frequent cracking of girders or beams encountered in environments highly exposed to changing weather conditions (swimming pools, industrial halls) are not only unaesthetic but most importantly destructive and irreversible. Therefore, it is necessary to develop the basis for guidelines that will allow the reduction of negative effects of moisture changes in timber elements during the normal usage not only by the additional specification in design standards but also by simplified construction and design solutions.

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