A THREE-DIMENSIONAL MOISTURE-STRESS FEM ANALYSIS FOR TIMBER STRUCTURES

Stefania Fortino and Tomi Toratti

ABSTRACT: In this paper a moisture-stress analysis based on a 3D orthotropic-viscoelastic-mechanosorptive model for wood is performed by using the Abaqus FEM code. The constitutive model and the needed equations of moisture flow are implemented into some Abaqus user subroutines. The method, which was previously validated with respect to existing experimental data on small wood specimens and glulam cross sections, is used for the moisture-stress analysis of a dowel-type joint under natural relative humidity.

KEYWORDS: Timber connections, Moisture transfer, Creep, Mechanosorption, Stress analysis, FEM, Abaqus.

1 INTRODUCTION

The serviceability and the safety of timber structures can be significantly affected by the combination of humidity history and mechanical loading [1,2]. Under service conditions of buildings, both the viscoelastic creep and the mechanosorptive effect can influence the durability of timber structures by inducing crack propagation and, in some extreme cases, the collapse of the structure [3,4,5].

Earlier literature widely gives information on moisture content of wood and its effects on mechanical performance. Moisture transfer and moisture induced strains and stresses have been the subject of many studies in the last decades, especially under artificial laboratory relative humidity and temperature conditions. However, only a few studies are focused on the moisture content effect in natural climate conditions. Ranta-Maunus explained the mechanical consequences of the moisture content in wood caused by a naturally varying climate in [6]. In function of the location of a building, the kind of building and its use, wood is not exposed to the same relative humidity. The mean value as well as the variation of moisture content of wood depends of these factors.

In the last decade, several computational methods have been introduced for the evaluation of moisture induced stresses in wood [7,8,9,10]. These models take into account the interaction between varying moisture and stress, called mehcanosorption or mechanosorptive creep, and sometimes neglect the effect of the viscoelastic creep, which is normally found at constant moisture contents.

For building purposes, timber elements are connected to each other by different kinds of connection. The most common connections are dowel joints, nail plates, nails and screws. In these connections, wood and steel are combined. In the presence of moisture content changes, the shrinkage can cause relatively high deformations of the wood elements but the stiffness of the steel components makes the connections rigid and may produce high values of the stresses, particularly in the cross grain direction [11]. When wood is extremely dry, the risk of cracking on the wood surface is strongly increased, especially if gradients of moisture content occur between the inner part and the outer part of the timber section. In some cases the induced moisture stresses in timber can even induce the collapse of the structure. In [12], 23% of the studied failure cases in timber structures were due to joint failures and 57% of them were dowel type connections. As one consequence, new failure modes have been introduced in the joint design of Eurocode 5 to account for timber shear block type failure [13]. However, moisture effects in connections are not deeply understood and need to be further investigated [14].

For the efficient design of timber structures, the formulation of a reliable 3D model for wood is important and the finite element code Abaqus represents a suitable computational tool for implementing constitutive models and for the simulation of three-dimensional coupled problems in engineering [15].

The aim of the present research work is to computationally estimate the levels of moisture induced stresses in timber connections and particularly in dowel-type joints which are used in long span structures. The used computational method is based on the three-dimensional orthotropic viscoelastic-mechanosortive model for wood presented and validated in [10] by comparisons with experimental data of small scale wood specimens and small glulam sections. In this approach

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the 3D Fick law is used for the moisture transfer modelling. Both the constitutive model and the surface moisture flow are implemented into user subroutines of Abaqus. A moisture-stress analysis is conducted by means of the Abaqus/Standard program. After describing the moisture-stress analysis, the improvement of the moisture diffusion modelling in the presence of high relative humidities is also suggested by exploiting the multi-Fickian approach proposed by Frandsen in [16]. In fact, a more accurate model for moisture transfer in wood could improve the evaluation of moisture induced stresses in timber structures under natural environmental conditions. A case study dowel-type connection under natural humidity conditions registered in Finland is computationally analyzed by using the single-Fickian approach [14]. The results show that variations of moisture content in timber connections can strongly increase the stresses in the direction perpendicular to the grain.

2 MOISTURE-STRESS ANALYSIS

2.1 CONSTITUTIVE MODEL

Wood is usually described as a continuum and homogeneous material with cylindrical orthotropy (see references in [17]). This is due to the particular growth mechanism in circular increments which produces the annual rings in the cross section and mainly longitudinally oriented cells (called tracheids at the microscopic level). The anisotropy in the cross sectional plane is due, at least partly, to the growth in radial cell rows which determines unbroken cell walls, called wood rays. Furthermore, because of the mainly longitudinally oriented cells, a larger anisotropy between the cross sectional plane and the longitudinal direction is observed. In this work the macroscopic level is defined as the scale of annual ring formation. However, the earlywood and the latewood rings are not considered as different materials. This results in an orthotropic material in which the radial (R) and the tangential (T) axes are oriented in directions where the earlywood and latewood rings are oriented in serial and in parallel directions in the cross section plane. Considering also the grain direction (L), the material at local level is orthotropic. In the following, a short description of the constitutive model is reported. For the details the reader is referred to [10]. According to [17] from a rheological point of view the material model used in this paper is composed of five deformation mechanisms in series which provide an additive decomposition of strain into elastic response, hygroexpansion, viscoelastic creep, recoverable mechanosorption and mechanosorptive irreversible creep:

$$\varepsilon = \varepsilon^e + \varepsilon^u + \varepsilon^{ve} + \varepsilon^{ms} + \varepsilon^{ms,irr}$$

(1)

where $\varepsilon$ is the total strain vector, $\varepsilon^e$ the elastic strain vector, $\varepsilon^u$ the hygroexpansion strain vector, $\varepsilon^{ve}$ the total viscoelastic strain vector, $\varepsilon^{ms}$ the recoverable mechanosorptive strain vector and $\varepsilon^{ms,irr}$ the irrecoverable mechanosorptive strain vector.

The elastic moduli are expressed as functions of density, temperature and moisture. In the examples analyzed in this paper, both the density and the temperature are assumed to be constant. Following [17] the moisture content $0<u<1$ is expressed as $u= (m-m_0)/m_0$ being $m$ the mass of the specimen and $m_0$ the mass of the specimen in absolute dry conditions.

Both the viscoelastic and the mechanosorptive recoverable creep are described through Kelvin type elements. The used viscoelastic model is an extension of the 1D formulation proposed by Toratti in [18] for parallel to grain direction and consists of a sum of Kelvin-type elemental deformations. The mechanosorptive model contains an irrecoverable part plus a series of Kelvin elements and is a combination of the 1D model introduced in [19] for cross grain direction and of the 1D model for longitudinal direction of wood presented in [18]. The extension of the previous models to 3D, based on three-dimensional elemental viscoelastic and mechanosorptive matrices, has been presented by the authors in [10]. In that paper, the method was validated by comparisons with experimental results relative to small scale wood specimens and small glulam sections under mechanical loading in both cases of constant and variable humidity conditions. The temperature was assumed to be constant because in service condition cases the temperature effect is considered to be very small compared to the moisture content effect [18]. All the material parameters and the elemental matrices of the model can be found in [10]. The routine for the viscoelastic-mechanosorptive creep is implemented into the user subroutine UMAT of the FEM code Abaqus.

2.2 MOISTURE TRANSFER MODEL

The moisture transfer is modeled by using the 3D Fick equation:

$$\frac{\partial u}{\partial t} = \nabla \cdot (D \cdot \nabla u)$$

(2)

where $u$ is the moisture content of wood and $D$ the diffusion matrix of moisture transfer. Note that this form of the Fick equation can be used when the density of wood is constant. For varying density, the variable concentration $c = \rho u$ instead of $u$ has to be considered as the potential (where $c$ represents the concentration in kg/m$^3$). In literature, the assumption of isotropic diffusion is usually made and only the diagonal coefficients of the matrix are considered to be nonzero. The flow from the air to the surface is given by the following equation (see references in [10]):

$$q_n = \rho_0 S (u_{air} - u_{surf})$$

(3)

where $q_n$ is the value of the flow across the boundary, $\rho_0$ is the wood density in absolute dry conditions, $S$ is the surface emissivity, $u_{surf}$ is the moisture content on the wood surface and $u_{air}$ the equilibrium moisture content of wood corresponding to the air humidity defined as follows:
where $S = 3.2 \times 10^{10} \exp (4a) \text{ m/s}$, $T$ is the temperature in Kelvin degrees and RH represents the relative humidity of the air.

The equations needed to describe the moisture flow in wood are implemented into the Abaqus user subroutine DFLUX, where both the flow magnitude and the rate of change of flow with respect to the current moisture content are calculated.

### 2.3 Implementation in Abaqus

The constitutive model is implemented into the user subroutine UMAT of Abaqus FEM code. At the beginning of the current time step $t_{n+1} = t_n + \Delta t$ of the stress analysis, the value of the total strain increment $\Delta \epsilon_{n+1}$, the values of total strain and stress, elemental viscoelastic strain $\epsilon_{ve}^i$ and elemental mechanosorptive strain $\epsilon_{me}^i$ are equal to those provided by the UMAT subroutine at the end of the previous time step. The total strain increment is written as

$$
\Delta \epsilon_{n+1} = \Delta \epsilon_{ex} + \Delta \epsilon_{in} + \sum_{i=1}^{p} \Delta \epsilon_{ei} + \sum_{j=1}^{q} \Delta \epsilon_{mj} + \Delta \epsilon_{mn,irr}
$$

The elastic strain increment is expressed as

$$
\Delta \epsilon_{ex} = \Delta \epsilon_{ex}^e + \Delta \epsilon_{ex}^u + \sum_{i=1}^{p} \Delta \epsilon_{ei}^e + \sum_{j=1}^{q} \Delta \epsilon_{mj}^e
$$

where $\mathbf{S}$ is the elastic compliance matrix and $\Delta \epsilon_{ex}$ represents the stress increment to be calculated at the current time step. The elastic compliance matrix is the following:

$$
\mathbf{S}^e = \begin{bmatrix}
\frac{1}{E_R} & -\frac{v_{IR}}{E_T} & -\frac{v_{IR}}{E_L} & 0 & 0 & 0 \\
-\frac{v_{IR}}{E_T} & \frac{1}{E_T} & 0 & 0 & 0 & 0 \\
-\frac{v_{IR}}{E_R} & \frac{v_{IR}}{E_T} & \frac{1}{E_L} & 0 & 0 & 0 \\
0 & 0 & 0 & \frac{1}{G_{RT}} & 0 & 0 \\
0 & 0 & 0 & 0 & \frac{1}{G_{RL}} & 0 \\
0 & 0 & 0 & 0 & 0 & \frac{1}{G_{TL}}
\end{bmatrix}
$$

where $E_i$ is the modulus of elasticity in the direction indicated by the subscript, $v_{ij}$ is the Poisson’s ratio and $G_{ij}$ is the shear modulus in the plane indicated by the subscript (see references in [10]):

$$
E_i = E_{ai} \left(1 + a_i (\rho - \rho_r) + b_i (T - T_r) + c_i (u - u_r)\right)
$$

$$
G_i = G_{ai} \left(1 + a_i (\rho - \rho_r) + b_i (T - T_r) + c_i (u - u_r)\right)
$$

where $E_{ai}$ and $G_{ai}$ are respectively the modulus of elasticity and the shear modulus both at the reference conditions of wood density $\rho_r$, moisture $u_r$, and temperature $T_r$. In [10] $\rho_r = 550 \text{ kg/m}^3$ for pine wood and $\rho_r = 450 \text{ kg/m}^3$ for spruce wood are assumed, $T_r = 20^\circ\text{C}$ and $u_r = 0.12$. Furthermore, $a_i = 0.0003$, $b_i = 0.007$ and $c_i = 2.6$ are dimensionless material parameters. Finally $\rho$, $T$, $u$ are the density, the temperature and the moisture content at the current time respectively.

The expressions of strain increments in Equation (6) are given by:

$$
\Delta \epsilon_{ex}^u = -S^e \Delta \sigma_{n+1} = b_i (T - T_r) + c_i (u - u_r)
$$

$$
\Delta \epsilon_{ex}^e = S^e \Delta \sigma_{ex, n+1}
$$

The hygroexpansion strain increment is obtained by the equation:

$$
\Delta \epsilon_{ex}^u = a_u \Delta \mu
$$

where $a_u$ is the hygroexpansion vector and $\Delta \mu$ is the moisture change at the beginning of the increment.

#### Table 1: Viscoelastic parameters

<table>
<thead>
<tr>
<th>$i$</th>
<th>$J_{in}^{ve} [-]$</th>
<th>$T_{in}^{ve} [\text{h}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.4</td>
<td>0.085</td>
</tr>
<tr>
<td>2</td>
<td>24</td>
<td>0.035</td>
</tr>
<tr>
<td>3</td>
<td>240</td>
<td>0.07</td>
</tr>
<tr>
<td>4</td>
<td>2400</td>
<td>0.2</td>
</tr>
</tbody>
</table>

Both the increment of viscoelastic and mechanosorptive strains are calculated by using the strain update algorithm originally proposed in [8]. By integrating the equation for viscoelasticity over time for the $i$-th Kelvin element, the following increment of elemental viscoelastic strain is obtained:

$$
\Delta \epsilon_{ve,i}^{ex} = S_{ve,i} \left( \frac{\Delta t}{\tau_{ve,i}^e} \right) \Delta \sigma_{ve,i} + \left(e_{ve,i} - S_{ve,i} \Delta \sigma_{ve,i} \right) \left(1 - \exp \left(-\frac{\Delta t}{\tau_{ve,i}^e}\right)\right)
$$

with the so-called viscoelastic time function defined as

$$
T_{i,n+1} = 1 - \frac{\Delta t}{\tau_{ve,i}^e} \left(1 - \exp \left(-\frac{\Delta t}{\tau_{ve,i}^e}\right)\right)
$$

and

$$
S_{ve,i}^{ex} = J_{ve,i}^e S_{ve,i}^{e}
$$

where $S_{ve,i}^{e}$ and $\tau_{ve,i}^e$ are the compliance and retardation time of the $i$-th viscoelastic element respectively, $\Delta t$ is the time increment and $e_{ve,i}^{ex}$ represents the elemental viscoelastic strain tensor from the previous step. $J_{ve,i}^e$ is a material parameter. $S_{ve,i}^{e}$ is the elastic
compliance matrix at reference moisture content and temperature. The values of viscoelastic parameters are reported in Table 1.

The recoverable mechanosorptive strain increment has the same mathematical form as the viscoelastic one:

$$\Delta \varepsilon_{j,n+1}^{ms} = S_{j,n+1}^{ms} T_{j,n+1} \left( \frac{\Delta \mu}{\tau_{j}^{ms}} \right) \Delta \sigma_{n+1} + \left( \varepsilon_{j,n}^{vs} - \sum_{j=1}^{n} \sigma_{j,n} \right) - \exp \left( \frac{-\mu}{\tau_{j}^{ms}} \right)$$

where $S_{j,n+1}^{ms}$ and $\tau_{j,n}^{ms}$ are the compliance matrix and retardation time of the $j$-th mechanosorptive element respectively, $\Delta \mu$ is the moisture content increment, $\varepsilon_{j,n}^{ms}$ represents the elemental mechanosorptive strain vector from the previous step and the mechanosorptive time function is:

$$T_{j,n+1} \left( \frac{\Delta \mu}{\tau_{j}^{ms}} \right) = 1 - \exp \left( \frac{-\mu}{\tau_{j}^{ms}} \right)$$

The recoverable mechanosorptive matrix and the values of mechanosorptive parameters are reported in [10]. The irrecoverable mechanosorptive strain increment is given by

$$\Delta \varepsilon_{n+1}^{ms,irr} = S_{n+1}^{ms,irr} \left| \Delta \mu \right|$$

where $S_{n+1}^{ms,irr}$ is the irrecoverable mechanosorptive compliance matrix, $\mu$ represents moisture content levels not attained during previous load history. The value of $\Delta \mu$ will then be zero for all moisture levels previously attained and equal to $\mu$-otherwise. The irrecoverable mechanosorptive matrix and the values of all parameters can be found in [10].

Because of the analogy between the moisture diffusion and the heat transfer analysis, the moisture-stress analysis for wood is performed by using the available temperature-displacement analysis of Abaqus Standard. The algorithm for moisture induced stress update at the current time step can be schematically listed in the following way:

1. The elastic compliance matrix $S^{e}$, the irrecoverable mechanosorptive compliance matrix $S^{ms,irr}$ and the strain increments which depend on the stress state at the beginning of the time increment are computed.

2. The elemental algorithmic tangent operator for viscoelastic creep $S_{i,n+1}^{ve}$ and the one for mechanosorption $S_{j,n+1}^{ms}$ (based on the elemental compliance matrices $S_{i,n}^{ve}$ and $S_{j,n}^{ms}$) are calculated.

3. The tangent operator of the whole model is computed:

$$C_{T} = \left( S^{e} + \sum_{i=1}^{p} S_{i,n+1}^{ve} + \sum_{j=1}^{q} S_{j,n+1}^{ms} \right)^{-1}$$

4. The new stress increment $\Delta \sigma_{n+1}$ and the elemental creep strain increments are calculated which are related through the following equation where $R_{i,n}^{ve}$ and $R_{j,n}^{ms}$ are functions of $u_{i,n}^{ve}$ and $u_{j,n}^{ms}$, respectively, and of the stress $\sigma_{n}$ at the previous time step:

$$\Delta \sigma_{n+1} = C_{T} : (\Delta \sigma_{n+1}^{e} - \Delta \sigma_{n+1}^{u} - \Delta \sigma_{n+1}^{ms,irr})$$

5. The updated values of total stress, viscoelastic strain and recoverable mechanosorptive strain are computed as:

$$\sigma_{n+1} = \sigma_{n} + \Delta \sigma_{n+1}$$

$$\varepsilon_{i,n+1}^{ve} = \varepsilon_{i,n}^{ve} + \Delta \varepsilon_{i,n+1}^{ve}$$

$$\varepsilon_{j,n+1}^{ms} = \varepsilon_{j,n}^{ms} + \Delta \varepsilon_{j,n+1}^{ms}$$

6. The final values of $\varepsilon_{i,n+1}^{ve}$ and $\varepsilon_{j,n+1}^{ms}$ are stored in the array STATEV of the UMAT subroutine and used for calculating the new quantities at the next time step.

7. The tangent operator of the model $C_{T}$ and the updated value of stress $\sigma_{n+1}$ are used in Abaqus/Standard for the stress analysis.

2.3.1 Extension of the algorithm for evaluation of hygrothermal stresses

The algorithm described above can be directly used in the context of a more general analysis for evaluating the stresses induced by both temperature and moisture changes in cases where the influence of temperature is important as, for example, the case of high-temperature drying modelling [17].

This kind of analysis can be performed with Abaqus by using a sequentially coupled method aimed to model both heat and moisture transfer and the induced stresses. The sequential analysis is basically performed in two steps:

1. a transient heat transfer analysis is conducted in order to simulate the temperature field, which is independent of the moisture field;

2. the coupled moisture-stress analysis described in the present work is performed but this time the mechanical quantities are dependent also on the temperature field calculated at step 1.

In the Abaqus code, the results of the first analysis can be easily read by writing suitable instructions into the input data file of the second analysis.

This approach is presented in a further joint paper by the present authors [20].

2.3.2 Extension of the algorithm for multi-Fickian modelling

The moisture transfer model can be improved by using a multi-Fickian approach. In fact, the real moisture transport process in wood is characterized by three phenomena: a) bound water diffusion, b) water vapor diffusion and c) coupling between the two phases of water through sorption. As pointed out by Frandsen et al. in [16], the single-Fickian approach is suitable at low relative humidities (RH lower than 80%), when bound
water diffusion is a slow process and the moisture transport in wood is mainly governed by water vapor diffusion. At higher relative humidities, the two-phase diffusion becomes important and this more complex phenomenon can be described by a multi-Fickian approach.

The implementation in the FEM code Abaqus can be done in two alternative ways:

- defining a new finite element based on the two variables of the coupled model through the user subroutine UEL;
- performing a sequential analysis which solves the two equations separately and corrects the obtained results until the convergence to experimental data is reached.

In the case of multi-Fickian diffusion analysis, a sequentially coupled method aimed to model both moisture transfer and induced stresses can be conducted in two steps:

1. the sequential multi-Fickian analysis is performed and the moisture content values are calculated as functions of the bound water concentration;
2. a stress analysis is performed where the mechanical quantities are calculated as functions of the moisture content values computed by the multi-Fickian analysis.

In the Abaqus code, the results of the previous analysis are read by writing suitable instructions into the input data file of the successive one. This development will be presented by the present authors in a future work.

3 APPLICATIONS TO DOWEL-TYPE CONNECTIONS

3.1 SERVICE CLIMATE CONDITIONS

The use of a building determines most of its climate conditions by influencing both the relative humidity and the temperature and, in some cases, providing aggressions by external components as chemicals, dust or mold [111]. In [21] the performance and long-term durability of timber structures under temperature and moisture loading were studied. The aim of that work was to control the humidity levels in construction of timber structures and wood products, in order to build high quality wood structures. The measurements of moisture in the “Forest Hall” of the Sibelius hall showed that in a heated room the relative humidity can be very low. In particular, during the winter time, the indoor average relative humidity is around RH=15% while, at the same time, the outdoor average relative humidity is around RH=85%. When wood is extremely dry as in the Sibelius hall, the risk of cracking on the wood surface is strongly increased. The moisture gradients cause stresses perpendicular to grain as explained by Ranta-Maunus in [6]. Since in service condition cases the temperature effects are found to be very small compared to the moisture content effect [18], the temperature is not taken into account in this study.

3.2 A CASE-STUDY

As a case-study, a 2-dowel connection used by Sjödin in [2] for other kind of experimental tests is analyzed under RH variation. The joint performance in the presence of glued-in rods is also studied (see Figure 1).

The material properties used for the analysis are

\[
\begin{align*}
E_R &= 600 \text{ MPa}, \\
E_t &= 12000 \text{ MPa}, \\
\nu_{Rt} &= 0.558, \\
\nu_{RT} &= 0.015, \\
G_{RT} &= 40 \text{ MPa}, \\
G_{RL} &= 700 \text{ MPa}, \\
G_{TL} &= 700 \text{ MPa}.
\end{align*}
\]

![Figure 1: Left: cylindrical coordinates in wood. Right: scheme of 2-dowel steel-to-timber connection, dimensions in millimeters (d = 12mm, F=3.5 kN).](image)

In the Abaqus numerical model used in this paper also the influence of the pith (origin) position has been taken into account by using a cylindrical coordinate system and specifying the material orientation as done in [22]. The influence of cylindrical coordinate systems on the stress calculation has been discussed for example in [23]. In Figure 1 the cylindrical coordinates in the plane RT (radial-tangential) are shown.

In the Abaqus model a 0.1 mm gap has been added in the contact area between wood and steel dowels, wood and steel plate and between dowels and steel plate in order to improve the convergence of the calculation. The contacts have been modelled by a hard contact pair with a penalty method in the tangential direction using a 0.4 penalty factor. The contact between rods and wood is modeled by a tie constraint. 3940 hexagonal elements C3D8T are used for meshing the wood part and hexagonal elements C3D8 for the steel plate and the dowel are chosen. The single-Fickian approach and the moisture-stress analysis are used.

![Figure 2: Abaqus model. Case with glued-in rods.](image)
3.2.1 Natural indoor relative humidity

The 2-dowel connection without glued-in rods is analyzed under natural indoor relative humidity measured in the Sibelius Hall (Figure 3). The wood member is realized in spruce glulam. A load $F = 3.5$ kN (25% of the experimental elastic limit) is considered to be applied for 1 year. The initial moisture content of wood was 12%. The start of the test corresponds to the beginning of July. The stresses during time are computed in four points around one of the holes (see Figure 4 and [14] for more details). The computational results of figures 4 and 5 show that the stresses perpendicular to grain exceed the characteristic values for glulam beams GL28c [13].

3.2.2 Natural outdoor relative humidity

The case of 2-dowel connection with glued-in rods is then analyzed. The connection has been loaded with a constant $F = 3.5$ kN which corresponds to 25% of the experimental elastic limit of the connection without glued-in rods. The connection has been exposed to a one-year outdoor relative humidity measured in Jyväskylä (Figure 6). The beginning of the test corresponds to January. Note that time 3230 hours is in summer time, so the moisture content of wood decreases during this period of the year. Instead, time 8000 hours is in winter time.
Figure 7 shows the stresses perpendicular to grain at a point around the hole in function of the time. The selected point is taken at around 7 mm from the surface of wood. It appears that the stresses are changed around the hole in presence of glued-in rods (see figures 8 and 9). An interesting effect is that a relevant part of the tension stresses are converted into compression stresses. This is important because the strength in the direction perpendicular to the grain is much higher in compression than in tension.

4 CONCLUSIONS

In this paper a numerical method for the evaluation of moisture induced stresses in wood is specialized for the analysis of timber connections under natural environmental conditions. The method, previously introduced in [10], is characterized by a three-dimensional orthotropic-viscoelastic-mechanosorptive constitutive model, a Fickian approach for moisture diffusion and an algorithm for moisture induced stress update. This approach was validated in [10] with respect to small wood specimens and glulam cross sections.

Because of the difficulty to find experimental values of moisture content and strain for wood specimens under natural humidity conditions from the literature, in the present work a case-study is numerically analyzed. The studied example is a 2-dowel type connection in steel and glulam wood [2] subjected to a natural indoor relative humidity previously measured in the Sibelius Hall (Finland) [21]. The same connection is studied in the presence of glued-in rods under natural outdoor relative humidity measured in Jyväskylä (Finland) [21]. In the first case the results show that the stresses perpendicular to grain exceed the characteristic values for glulam beams indicated by the Eurocode 5. In the second case a relevant part of the tension stresses are converted into compression stresses.

Because of the interesting results in terms of stresses, this study points out: a) the necessity to collect more experimental data for better validating the numerical method under real environmental conditions and b) the importance to develop more advanced approaches for moisture transfer modelling in order to accurately evaluate moisture induced stresses for the design of high performance connections in real size timber connections under service conditions of buildings [16].

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REFERENCES


