LONG TERM BEHAVIOUR OF A TWO-WAY SPANNING TIMBER CONCRETE COMPOSITE SLAB WITH STEEL TUBE CONNECTOR

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ABSTRACT: Timber-concrete composite (TCC) plays increasingly important roles in today's timber construction. Using timber in the tension zone and concrete in the compression zone uses both materials to their strengths. A novel two-way spanning TCC slab using steel tubes as connectors of the timber and the concrete members was developed at ETH Zurich. As both, concrete and timber have independent long-term behaviours the long-term effects of the slab system are to be determined. This paper discusses the set-up of planned long-term tests and the development of a finite element model to describe the long-term behaviour of the slab system that then can be verified once enough data is acquired.

KEYWORDS: Timber-concrete-composite, TCC, Long-term, Numerical modelling, Steel tube connector, Biaxial

1 INTRODUCTION

Due to the ongoing discussions about the climate in recent years, sustainable construction has become increasingly important. The increasing use of wood in construction leads to a long-term storage of CO_2 and a lower expenditure of gray energy. Since it is estimated that 4 - 7 % of global anthropogenic CO_2 emissions come from cement production, it is not sufficient to modify only manufacturing methods or cement composition [1].

As floor slabs account for one of the largest shares of volume in any building and have been made largely out of reinforced concrete a way of addressing this concern is the development of more climate-friendly alternative systems. Today slabs often are made of high-performance timber products as cross-laminated timber, dowel-laminated timber or timber concrete composite (TCC) [2]. Uniaxial line-bearing timber-concrete composite slabs have already been researched with extensive experimental and numerical investigations, and reliable design bases have been developed [3] [4] [5].

With the current increase in demand for wooden high-rise buildings, the need for slab systems that enable their construction is also growing. In addition to the load-bearing capacity, important requirements for the ceiling system include the need for architectural freedom concerning the floor plan, the thickness and the weight of the slab. Architectural freedom can be achieved by using a two-way spanning system and low weight and thickness of a slab directly translate to a more efficient building as less foundation measures are needed and more usable floor area can be achieved with the same amount of total building height.

With these boundary conditions in mind, a novel biaxial-bearing TCC slab system was developed at ETH Zürich using steel tubes as connectors. The system consists of a 60-100mm thick timber member. Depending on the needed performance, this timber member consists out of beech laminated veneer lumber (LVL), cross-laminated timber (CLT) or a newly developed intermediate product of both using 10mm thin birch lamellas. The concrete member is 90mm thick. The novelty of the slab consists in the non-bearing intermediate layer that separates timber and concrete and is filled with cellulose, stone wool. A heavier recycled material can be used as filling instead if it is needed to comply with sound or vibration criteria. The sheer connection between the timber and concrete layers consists of steel tubes. The general concept of the system is depicted in Figure 1.

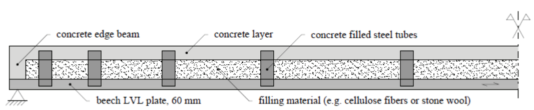

Figure 1: *Concept of the developed TCC slab system with steel tube connector* ***[6]****.*

As a common design problem of timber and TCC slabs are the deflection criteria that need to fulfill a given serviceability limit state (SLS) enforced by structural design guidelines [7] and both concrete and timber have a rheological behaviour, the long-term properties of the slab system have to be investigated.

2 METHODS

2.1 LONG-TERM TESTS

To investigate the long-term behaviour of the slab system long-term tests are investigated in a climate-controlled bunker chamber in Niderweningen, Switzerland. The specimens installed include:

- Uniaxial bending specimens for different two materialisations in both loading directions and 3 loading levels

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- Several connection specimens in a double shear push-out layout to investigate the behaviour on a connection level, with different types of connection layouts,
- bending tests on timber-only beams to investigate the long-term behaviour of different timber materialisations

Space limitations prevent long-term investigations on a biaxial-bearing specimen.

2.1.1 Bending specimens design

The beech LVL configurations timber member consists of a 60mm thick beech LVL (BauBuche Q) plate. For both loading directions (longitudinal and transverse to grain) 5000mm long, 600mm wide and 240mm high bending specimens on three different loading levels in each grain direction are investigated. The steel tubes are arranged according to the expected shear force distribution. The outer steel tube diameter is 101.6mm with a wall thickness of 3.6mm. The steel tubes are embedded into the timber member using a 2mm thick layer of 2C-epoxy resin. The embedment depth of the steel tube into the timber member is 50mm. The embedment depth of the steel tube into the concrete (C40/50) is 60mm. Except for the concrete layer everything was prefabricated by Implenia Holzbau AG. The specimens tested in transverse to grain direction additionally feature two BARTEC connections that connect the timber members, as the maximal production width of BauBuche Q is 1850mm. Therefore, 3 individual pieces have to be connected for the total 5000mm lenght. The layout and dimensions for the specimens in the longitudinal direction are depicted in Figure 23.

2.1.2 Push-out specimens design

As previously conducted short-term tests conducted showed [6], that the global slab behaviour is highly influenced by the local connection behaviour, investigations on the connection level are carried out. For this investigation adapted versions of a double shear push-out test with an appearance as depicted in Figure 2 are used. The outer dimensions of the specimens measure 480 x 400 x 220 mm. With these specimens, the influence on the connection configuration is investigated. These tests include investigations on:

- the type of glue used,
- the thickness of the glue line,
- the local behaviour of different materialisations,
- the embedment depth in eighter layers and
- the influence of the steel tube diameter.

The push-out specimens are carried out in a symmetrical single-material set-up to be able to retrieve the local stiffness behaviour for every embedment type. The combined connection behaviour can be later predicted with a procedure developed by Kreis [6].

Figure 2:*Example of push-out specimen in beech LVL*

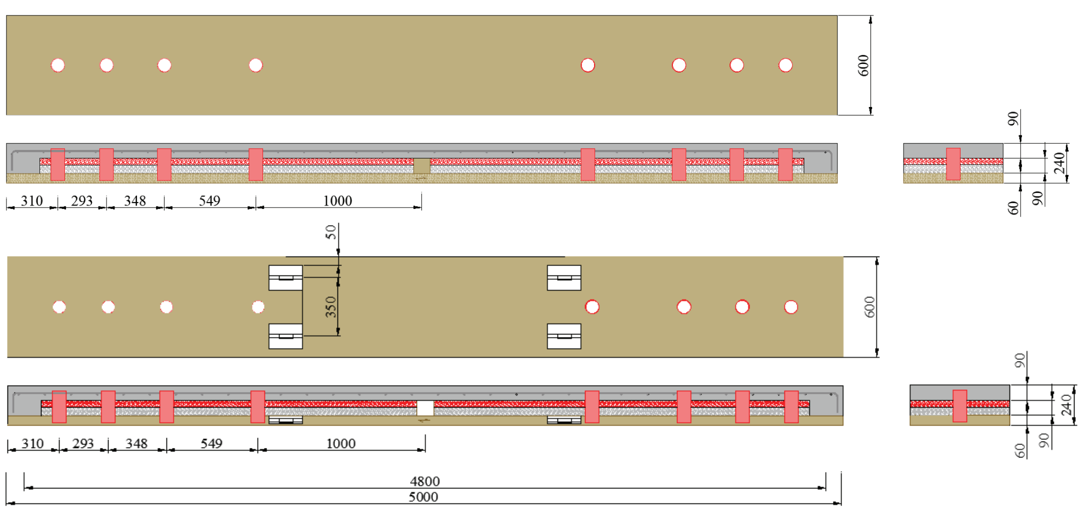

Figure 3: *Uniaxial bending specimen series with dimension longitudinal (top) and transverse (bottom) to grain loading direction.*

2.2 NUMERICAL MODELLING

2.2.1 Software and Subroutines

As the adjustable parameters of the slab systems are extensive and the number of possible experimental tests limited a numerical a parametric simulation model was developed for a 3D analysis. The commercial software Abaqus FEA of the company Dassault Systèmes was used. For the Finite Element analysis, the Abaqus/Standard solver was used. The choice to use Abaqus for the modelling process was strengthened by the fact that the user can adapt functionalities with the use of user subroutines. For the modelling process described in this work the user subroutines UMAT and UEXPAN were applied to define user specific material behaviour and thermal expansion.

2.2.2 System

A separate model for the uniaxial bending and the push-out set-up was developed to be able to simulate the outcomes on both levels of detail. The model of the connection level (push-out) is primarily used to simulate the (non-linear) short-term behaviour that the system shows for short-term push-out tests. With this data the short-term behaviour of the whole slab can be predicted reliably as shown by Kreis [6]. The assembly and boundary conditions are shown in Figure 5. Symmetry conditions help to reduce the total calculation costs.

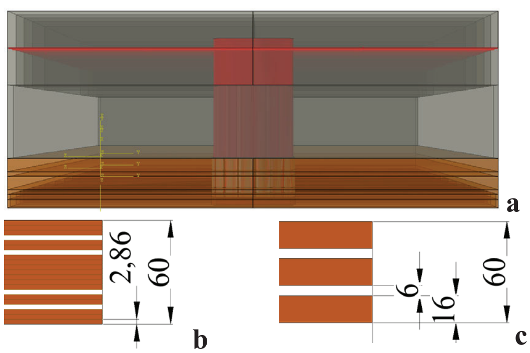

Figure 4:(a) face view of the model, (b)timber member structure in reality and (c)model simplification, with layers loaded parallel to grain in brown layers loaded transverse to grain in white.

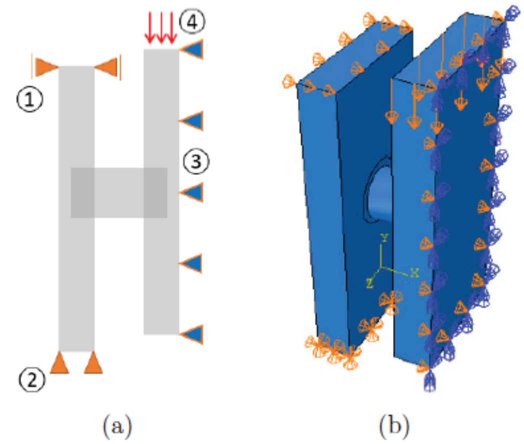

Figure 5 *(a) Boundary conditions: ①support in horizontal direction ② support in vertical, horizontal and out of planel direction ③symmetry conditions ④loading (b) boundary conditions on the 3D model.*

For long-term modelling primarily the bending-test set-up is used. If the whole slab is simulated the time-dependent rheological processing can be captured and processed. Further, they can be translated into a beam midspan deflection, which can be compared to hand calculations or SLS conditions.

The bending set-up model with the configuration using beech-LVL as a timber-member is visualized in Figure 6. This configuration is exemplatory used for the further proceedings of this work. The model consists of an LVL-plate, eight steel-tubes, gluelines connecting steel and timber and the concrete layer that is reinforced with shrinkage reinforcement-bars.

To model the LVL layer some simplifications are made. For numeric reasons the real structure of the beech LVL shown in Figure 4b is simplified with the approach depicted in Figure 4c. The four transverse layers are reduced to two so a simpler 5-layered structure is achieved.

The individually modelled lamellas of the timber member, the steel tubes and the timber, the glue-lines and the concrete layer are connected with tie-constraints with the other parts they are connecing with respectively. For the mechanical modelling, this leads to connections with

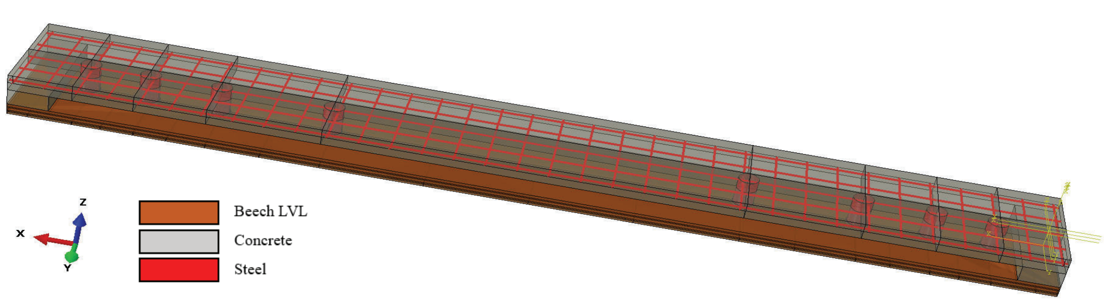

Figure 6: *Visualisation of the model in the uniaxial bending set-up.*

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higher stiffnesses as in reality. For the purpose of long-term modelling this is assumed to be acceptable as a lot of computing cost can be saved.

2.2.3 Material models

As both main materials (timber and concrete) used have distinct but different long-term behaviour according material models have to be introduced for the finite element (FE) simulation.

To describe the complex time-, load- and moisture dependent behaviour of european beech (*fagus sylvatica*) the rheological model of Hassani [8] is used. The model was numerically implemented via a UMAT subroutine, as the available Abaqus tools could not provide the needed material behaviour. The basis of the model lays in the implementation of a series of serial-switched Kevin-Voigt-elements, representing the elastic and plastic strains, hygroexpansion (swelling and shrinking) and the strains resulting from visco-elastic and mechano-sorptive creep (see Figure 7).

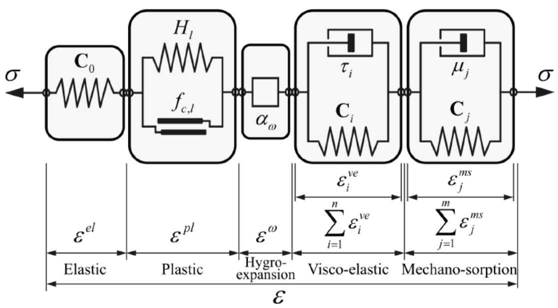

Figure 7:*Rheological material model to describe the time-dependent behaviour of timber* ***[8]****.*

Because of the serial switched strains in the system the total strains can be calculated with Equation (1):

$$\epsilon = \epsilon^{el} + \epsilon^{pl} + \epsilon^{\omega} + \sum_{i=1}^{n} \epsilon_i^{ve} + \sum_{j=1}^{n} \epsilon_j^{ms} \tag{1}$$

A more detailed description of the numerical implementation of the timber member will not be given in this paper.

The E-modulus of concrete is assumed to be linear-elastic for the model. Modelling a plastic material behaviour in concrete would be possible, but it is assumed that the stresses in the concrete will not reach the plastic range for the this application. A plastic model would unnecessarily increase the already high computational costs. Due to continuous hydration of concrete the E-modulus of concrete is time-dependent. The expected development is described with the CEB-FIB-90 model [9] in Equations (2) – (4)

$$E_{ci}(t) = \beta_E(t) \cdot E_{ct} \tag{2}$$

$$\beta_E(t) = \sqrt{\beta_{cc}(t)} \tag{3}$$

$$\beta_{cc}(t) = e^{s\left(1-\sqrt{\frac{28}{t}}\right)} \tag{4}$$

with s=0.2 and E_{ci} = E-modulus after 28 days.

The modelling of the shrinking and creep- behaviour that is part of the long-term effects of concrete is done by implementing the CEB-FIB-90-Modell that is part of EC 2 [10]. This is numerically done using the UEXPAN subroutine developed by Hampel [11]. With this subroutine the strains coming from shrinking and creep effects calculated after EC2 can be introduced into the model for each time-step. For this the creep and shrinkage effects have to be rewritten as increments $\Delta\epsilon$ that is calculated for each time step $\Delta t = t_n - t_{n-1}$

A more detailed description of the numerical implementation of concrete will not be given in this paper.

2.2.4 Loads

The long-term simulation is made for a time span of 61 months to simulate the first five years after the experimental set-up additional to the first 28day hardening time after concreting. In the first 28 days only 10% of the dead load is simulated as exterior load for convergence purposes. After 28 days the full dead load and an additional areal load is enabled to act on the model. For the exemplatory model presented in this paper the areal load sums up to a total of 3.5 kN/m² representing the 2 kN/m² live load and the additional weight of the slab structure above the load-bearing layer of 1.5 kN/m². The changing moisture content of the air that leads to changing moisture contents in the timber due to its hygroscopic behaviour is simplified. During the simulation process the exposed surfaces of the timber specimen is subjected to a changing surface moisture content that is varying with a sinoical function between 8% and 12%. This is representing a effective moisture content change of 4% in the timber during a year. In Figure 8 the loading conditions for the first 2 years is shown.

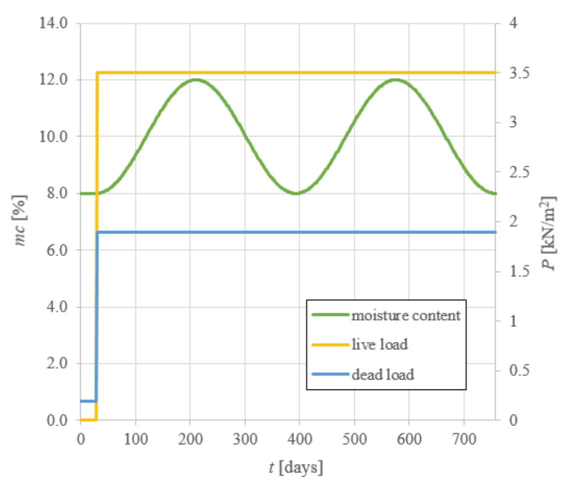

Figure 8: *Loads and subjected moisture content to exposed surfaces for the first 2 years of the model.*

2.2.5 Modelling process and elements

As the moisture content distribution within the timber over time is initially unknown, first an analysis is made with the only external load being the induced moisture content on the exposed timber surfaces. For this process DC3D20 elements are used. In this step the moisture content for each node in the timber member for the total simulation time of 5 years is calculated.

In a second step a mechanical analysis can be carried out using C3D20R Elements. In this second step all loads and boundary conditions are enabled. The moisture content needed to calculate the additional stresses and strains considering the rheologicals effects in the timber are read from the output- file of the first analysis.

3 RESULTS

3.1 MOISTURE DISTRIBUTION

The resulting moisture distribution for the first simulated year is shown in Figure 10. At day 0 the initially defined moisture content of 8% throughout the whole timber member is visible. After 198 days the moister content induced to the models exposed surfaces reaches its maximum of 12%. It can be observed that somewhere around the 300 day mark a maximal moisture content just short of 11% is reached in the middle of the timber member. It can be seen, that when all 4 sides of the timber member are exposed to a seasonal change in relative humidity in the environment, the whole timber cross-section is subjected to significant changes in equivalent moisture contents.

3.2 MIDSPAN DEFLECTIONS

The simulated midspan deflections are displayed in Figure 9. It can be observed, that the changing moisture content has a high influence on the midspan deflections. The initial high displacements due to initial loading appear to slow down after 2 years of simulation. Going forward a slight increase in midspan deflection is observed every year.

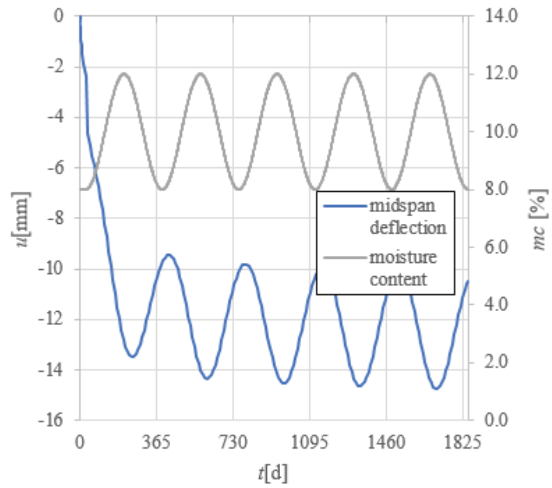

Figure 9:*Midspan deflections of the slab system in relation to the moisture content of the timber member.*

3.3 MIDSPAN STRAINS

For a point on the bottom of the timber member the strain componets are displayed in Figure 11. The total strains consist of shares from elastic, visco-elastic, swelling/shrinkage and mechano-sorptive strains. It can be observed that the swelling and shrinking component is the highest compared to the other strain components. After that the visco-elastic creep component appears to have the second highest influence. The mechano-sorptive creep has the least influence on the total strains even with the high moisture change during a simulated year.
In Figure 12 the midspan strains in a representative point on the concrete member area are shown. The total strains consist of shares from creep shrinkage and elastic strains.

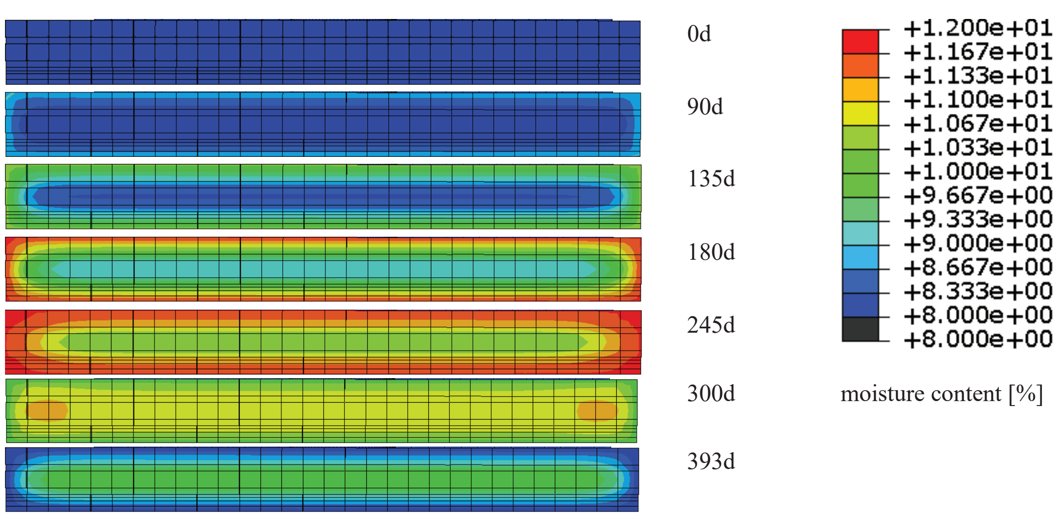

Figure 10: *Moisture distribution at midspan inside in the timber member with four exposed sides during the first year of simulation.*

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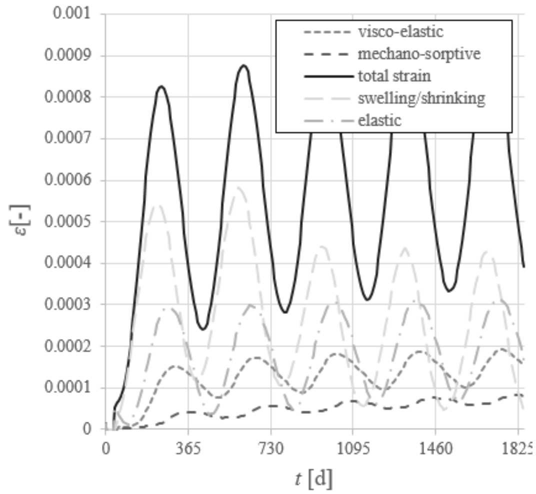

Figure 11: *Visualisation of the strains components at midspan in the timber member*

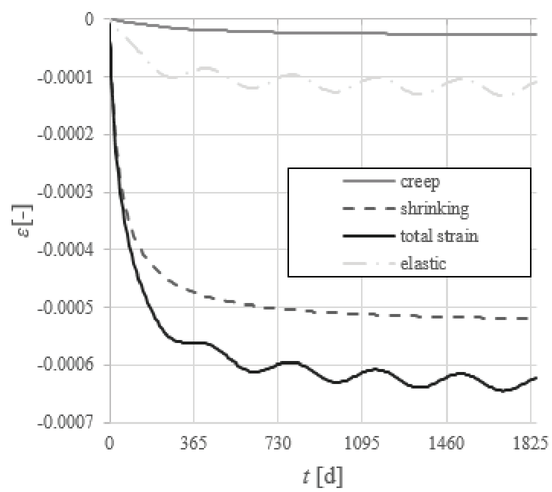

Figure 12: *Visualisation of the strains components at midspan in the topsurface of concrete member.*

4 DISCUSSION

4.1 MOISTURE DISTRIBUTION

The assumption of a 4-sided exposure to moisture of the timber member in the testing set-up can be justified by the fact, that contrary to an area-wide system (real case) the sides of the specimen are exposed. Additionally, the filling material of the interlayer is permeable to moisture. With this chosen 4-sided exposure the moisture content inside the timber member changes almost uniformly. As in the real slab system only exposure from the bottom side is to be expected it has to be accounted for in the proceeding investigations.

It has to be noted, that the way the LVL plate is modelled could have a big bias on the resulting moisture distribution. The simplifications used do not take into account the possible reduction in moisture transport through the glue lines. Especially in a LVL, where the veneers are only 3-4 mm thick, this can have a big influence on the resulting moisture distribution. It is assumed that in reality the moisture is less able to spread through the thickness of the board. This has especially an influence on the result when only one-sided (real case szenario) moisture penetration can take place.

Furthermore, the exact moisture transport conditions in beech LVL is still unknown and has yet to be investigated.

4.2 MIDSPAN DEFLECTIONS

In the first 28 days of the simulation the shrinking of the concrete member presumably is the driving factor for a large amount if the initial midspan deflections. Reducing these shrinking deformations to a minimum within the production process has to be a goal. It is obvious that also the changing moisture content has a big influence on the midspan deflections. The assumed 4% change in yearly moisture change within the timber member is with high probability on the safe side. It is assumed that in reality the resulting moisture exchange is much lower. Nevertheless, it is shown that the moisture content at the time of installation can have a big influence on the total deflections and has to be considered.

4.3 MIDSPAN STRAINS

The high amplitudes of the swelling and shrinking strains in the timber member stand in direct context with the changing moisture content. Because of the 4-side exposed timber specimen moisture exchange happens rapidly and thus high swelling and shrinking is simulated. Only a slight time deviation between the maximally induced moisture and maximal swelling and shrinking components is registered. It is assumed, that with only one side exposed to moisture change, this deviation in time will be bigger.

For the concrete member, the biggest influence on the total strains is coming from shrinkage. After five years the total value for the shrinkage strain corresponds to the analytical solution of EC 2 which is $5{,}13 \cdot 10^{-4}$. This is the result of autogenic and drying shrinkage only being dependent on the time. In the contrary creep is dependent on the elastic strains at the respective time. Through creep the concrete escapes external loads and thus reduces elastic strains.

4.4 GENERAL DISCUSSION

The manual calculation of the presented slab system is based on many assumptions due to the complex geometry and the only partially explored connection. Because the model also still has to make do with many assumptions and not enough experimental data could be collected yet, no verification and validation of the model can be shown within the scope of this work. It is therefore to be noted that up to this point the model shown is only theoretical.

Nevertheless, the model can be used to further understand the system and its general behaviour.

For a reliable simulation of the long-term behaviour of beech LVL, input-material parameters are also missing. Up to now, one has to make do with solid wood parameters for certain parameters that influence the long-term behaviour. However, it can be argued if beech LVL has a lot in common with solid beech wood, if one takes a closer look at its production process.

In addition, further studies with Hassani's material model are necessary. No validation of the model is available for a simulation period longer than one year [8].

5 CONCLUSION

It has to be stated that the presented results exemplify what the model output can be and can not be regarded as concluding. The main task of this paper is to show to opportunities and challenges of long-term modelling with Abaqus.

Modelling such a complex system seems in many parts a balancing act between the level of detail and the introduction of necessary simplifications to keep the computational costs under control.

In the next step acquired experimental data will be used to validate the model for the push-out and uniaxial bending set-up.

Further ahead lies the challenge to adapt the model to an actual biaxial bearing system. Although the system can also be used uniaxial-only it’s full potential is only reached with the biaxial application and it’s additional influence on the load-bearing behaviour.

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