Moisture diffusion in wood – Experimental and numerical investigations

Bettina Franke[1], Steffen Franke[2], Marcus Schiere[3], Andreas Müller[4]

ABSTRACT: The hygroscopic behaviour of wood leads to changes in the physical and mechanical properties. The correct estimation of the moisture content is important for the design and life cycle of timber structures. Therefore experimental test series were performed to determine the moisture content distribution over the cross section as a function of loading duration, respecting the glue lines of glulam and block glued cross sections. Alongside, numerical simulations of the moisture diffusion process were set up and validated with the experimental test series. The correlation of the numerical simulation with the reality offers guidance in the design of timber structures.

KEYWORDS: Wood, Moisture transport, Moisture gradient, Monitoring, Simulation

1 INTRODUCTION

Timber constructions are exposed to the variation of the ambient climate. Wood is a hygroscopic material and reacts in a change of the moisture content, mainly due to the change of the air temperature and relative humidity. The moisture content influences the physical and mechanical properties. Therefore, the correct estimation of the moisture content is important for the design and life cycle of timber structures. The design standards consider this behaviour by three different service classes (SC) according to the annual average moisture content. The assignment of timber elements to one service class according to the ambient climate condition is one important step during design.

Moisture diffusion is not constant over the cross section due to daily, weekly or seasonal changes of the climate situation. Subsequently, moisture gradients develop. The moisture gradients produce stresses over the cross sections which can result in cracked beams, Dietsch et al. (2014). For example, an increase of the moisture content leads to moisture induced transverse tension stresses in the inner part of the cross section. If these stresses exceed the very low tension strength perpendicular to grain of wood, the cross section can crack and lead to a reduction of the load carrying capacity for transverse tension or shear. These cracks are not visible during maintenance, inspection, and assessments periods.

Currently, the planning engineer respects this complex hygroscopic behaviour of wood in the design by the application of service classes. But questions rise: What happens over the life time of a construction or within exposed timber bridges? Therefore experimental test series were carried out for the classification of the moisture diffusion over the cross section and numerical simulations were done for the comparison and evaluation.

2 MATERIAL AND METHOD

2.1 MATERIAL

One glued laminated timber member 200/600/4000 mm of soft wood without finger joints was produced, and all specimens were cut from this member, as shown in Figure 6. The thickness of each lamella was 40 mm and the average density was 443 kg/m^3. The production was according to the SN EN 14080:2013 using the adhesives Kaurarim® 683 and Kaurarim® hardener 686.

The specimens were first conditioned at normal climate (20°C and 65 % relative humidity) until equilibrium moisture content (EMC) of 12 M% [3] was reached and loaded by moisture in a climate chamber afterwards.

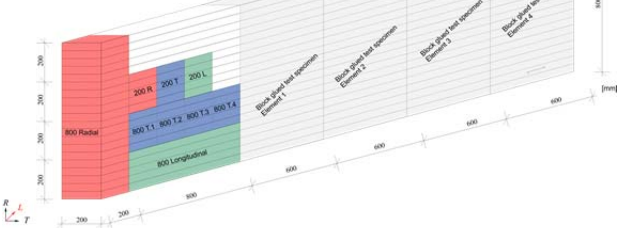

Figure 1: *Cutting plan of glued laminated timber member*

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2.2 EXPERIMENTAL TEST PROGRAM

For the observation of the developing moisture content over the cross section, the test series were prepared in the three material axes: radial (R), tangential (T) and longitudinal (L). Furthermore two different sizes (200/200/200 mm and 200/200/800 mm) per material axes were carried out, see Figure 2. The side faces of the test specimens were sealed, so that the moisture diffusion only took place in one material direction. On each specimen, gages at a depth of 25, 45, 70 and 100 mm from the unsealed surfaces were implemented. For the test series with 200/200/800 mm in size, additional measuring points in a depth of 150, 200, 300 and 400 mm were installed. The specimens were conditioned at 20 °C and 65% relative humidity and loaded with a 95 % relative humidity afterwards for a period of about 12 months.

The electrical resistance method was used for the determination of the moisture content using a pair of

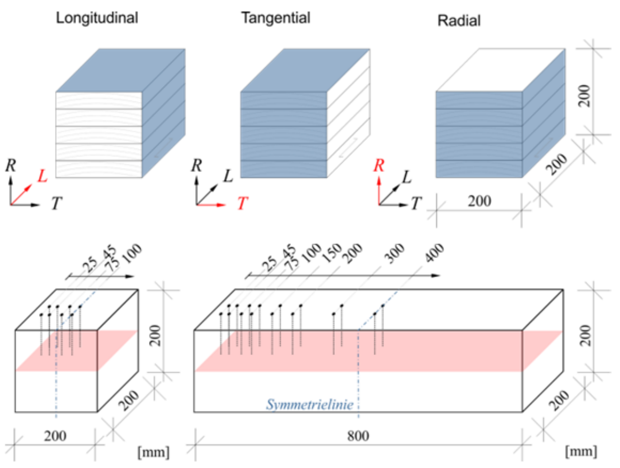

Figure 2: *Test specimens with sealed surfaces in blue (top) and position of measuring points for the 200 mm and 800 mm long specimens (bottom)*

Figure 3: *Moisture content measuring sensor, insulated stainless steel screws*

Figure 4: *Climate conditioning of specimen*

insulated stainless steel screws as sensor. A Thermofox and Gigamodul from Scanntronik Murgauer GmbH were used to log measurements every 6 hours.

2.3 MOISTURE DIFFUSION

Transient moisture diffusion is defined through Fick's second law:

$$\frac{\partial u}{\partial t} = D\,\frac{\partial^2 u}{\partial t^2} \qquad (1)$$

Analytical [7], [8] and numerical methods [9], [10] have been proposed and developed to solve this differential equation. The analytical equations consist of a short term solution and a long term solution [5].

The analytical solution showed some drawbacks. To solve the equation analytically, the diffusion parameter *D* must remain constant, whereas it is known that *D* also depends on the moisture content. Secondly, the starting condition requires the moisture content to be in equilibrium and the final condition to remain constant throughout the entire simulation. Finally, literature recommends that Fick's second law is used for wetting only [12], as some extra relations need to be added to equation (1) to properly model drying processes or cyclic moisture content changes [13]. Analytical equations for these processes are not available.

Numerical methods are more flexible, but often take more effort to implement. FE-methods allow for moisture diffusion calculations through the mathematical analogy between moisture diffusion and temperature flux.

3 RESULTS

3.1 EQUILIBRIUM MOISTURE CONTENT

Sorption isotherms were obtained from literature to determine the equilibrium moisture content to which the specimens were conditioned and loaded afterwards. The starting point was to use sorption isotherms defined by Simpson [3]. The author determined equations through which the equilibrium moisture content could be calculated as a function of temperature and relative humidity. These isotherms are based on Sitka spruce species, see continuous line of Figure 5. According to these sorption isotherms, the corresponding EMCs to which the specimens were conditioned and loaded were

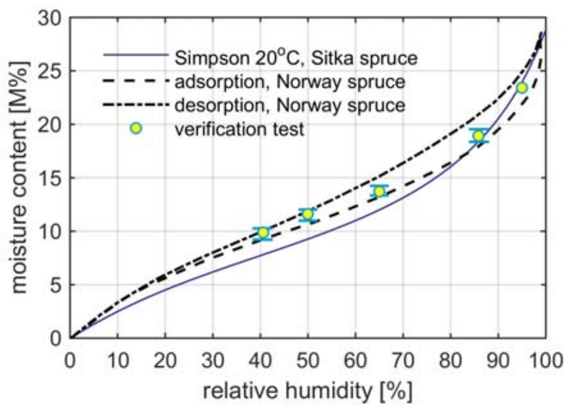

Figure 5: *Comparison of sorption isotherms for different species by different authors*

12 M% and 24 M%, respectively. The sorption isotherms were later compared to ad- and desorption isotherms [4] obtained for Norway spruce (origin Central Europe), illustrated with the dashed and dash-dotted lines. Finally, some tests with small specimens conditioned at different relative humidities were performed to verify the isotherms of the used glulam [5]. These results are indicated with the circles in the same diagram.

The distribution of the single values and curves shows that, at regular relative humidities, the equilibrium moisture content can be underestimated by a couple of percentages when Simpson's sorption isotherms are used. Although potentially erroneous for comparisons with experiments, they are used due to their mathematical basis.

3.2 RESULTS FOR THE MOISTURE DISTRIBUTION OF THE EXPERIMENTAL TEST SERIES

The moisture distribution over the measuring period and cross section observed for the 200/200/200 mm test series are summarized in Figure 6. The diagrams include one curve for each measuring point. In longitudinal direction the curves reach soon a plateau. However in radial and tangential direction an increase of the moisture content is still present, illustrating the slower process of wetting. It must be pointed out that the plateau reached is at 20 M%, whereas the equilibrium moist content according the climate 20°/95% is 24 M%. The oven dry method carried out after the tests finalised confirm a moisture content of 24 M%. It is expected that an additional time dependent calibration factor should be determined due to observed corrosion of the screws as well.

The climate chamber shortly broke down within the measuring period, during which the ambient relative humidity could not be controlled. The time period is shaded grey in the diagram. For the experimental test series 200/200/800 mm similar results could be observed, as summarized in [6].

The distribution of the moisture content over the cross section shows a clear gradient from the surface to the inner part in all three material axes. The increase of the

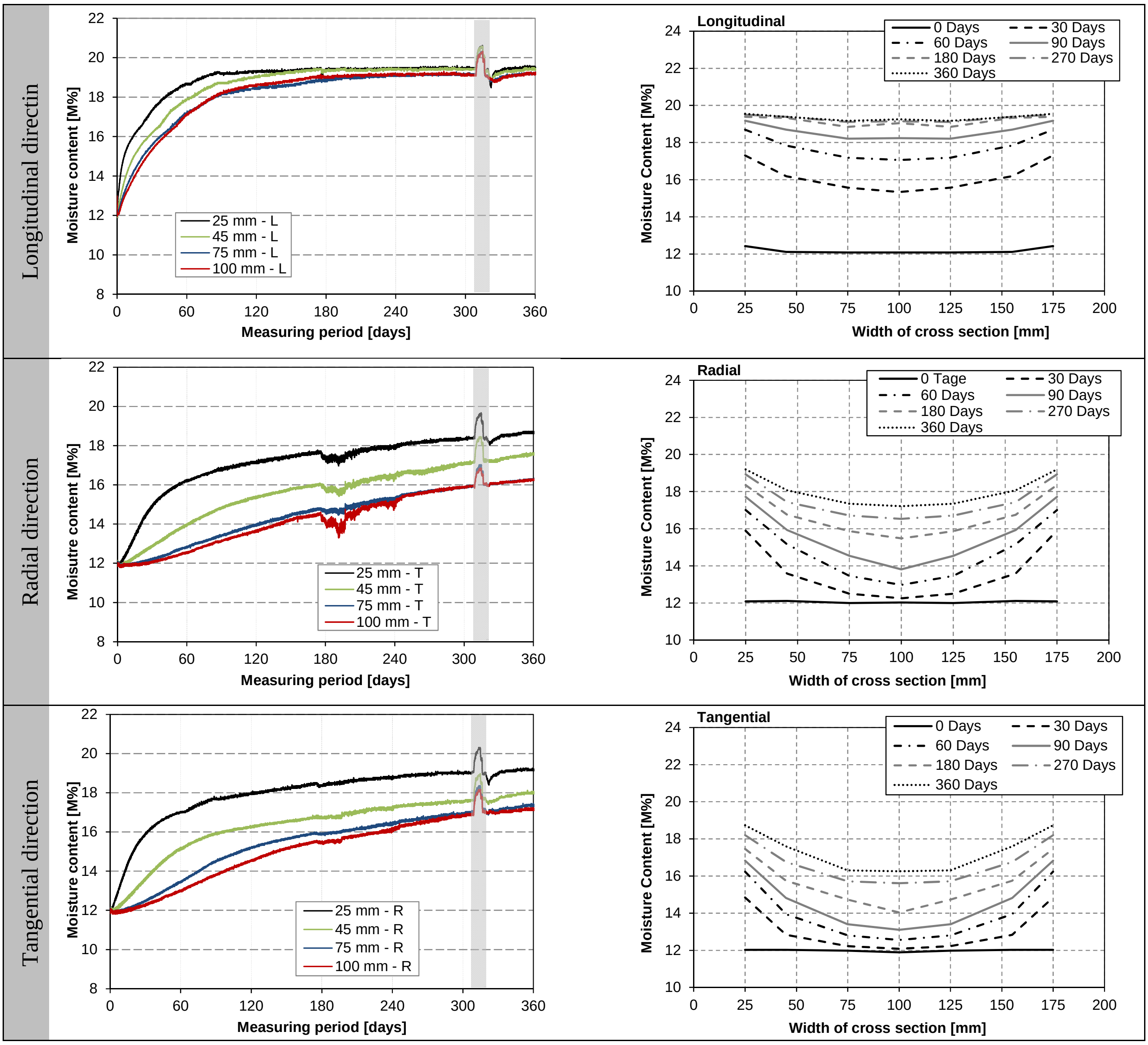

__Figure 6:__ Moisture content development over time and cross section for the three material directions

gradient depends on the diffusion direction. The question rises how long does it takes to get a uniform distribution over the cross section in radial and tangential direction and how big is the influence is of the gradient on the stress-strain-behaviour? The numerical simulations were set up in an effort to answer these questions.

3.3 EXPERIMENTAL DIFFUSION PARAMETERS

Fick's second law in Eq. 1 was used and modified to enable numerical derivation of the diffusion parameters for the different material directions [5]. The calculated diffusion parameters overlap those found in literature [13] and were calculated for the range from 12% to 20% MC at 20°C. The derived parameters, listed in Table 1, were used in the simulations with FE mentioned later in Figure 9 and Figure 10. The diffusion values are visualised in Figure 7.

The difference between the experimentally derived radial and tangential diffusion parameter is higher than expected, as differences are suggested to be about 15% or even negligible [7]. Apart from that, sources like [16] suggest that glue lines should actually block the vapour diffusion in the radial material direction, which means that the radial diffusion parameter should be (much) lower than the tangential one. However, most of those researches focused on other wood products than glulam.

Table 1: *Derived experimental diffusion parameters*

Direction	Value [m^2/s]
Longitudinal, D_l	10.42e-10
Radial, D_r	2.89e-10
Tangential, D_t	1.61e-10

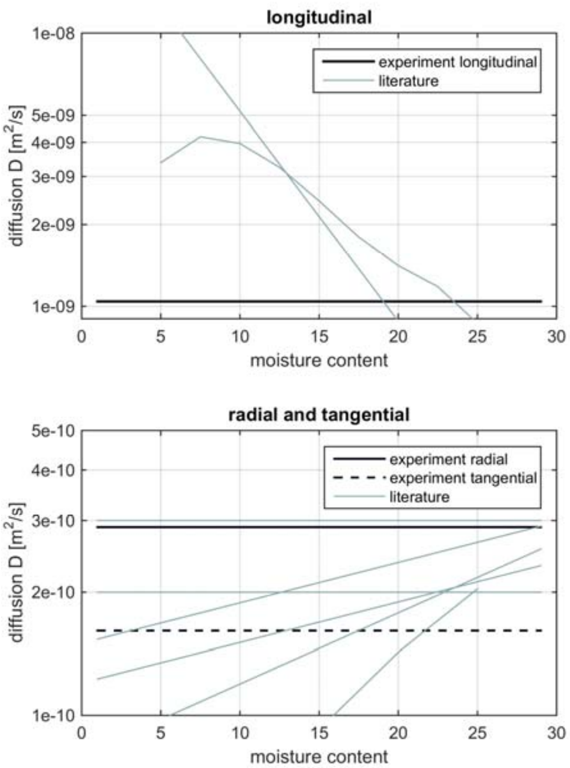

Figure 7: *Visual comparison of the experimental (thick black) and literature (grey) diffusion values*

As is observed as well from Figure 7, most derived diffusion parameters indicate that there is a correlation between the magnitude of the diffusion value and moisture content, negative from transport parallel to the grain and positive for transport perpendicular to the grain. This was not derived for the experimental values as they actually only covered a small range of moisture contents. Future efforts will focus on deriving moisture content dependent values.

3.4 NUMERICAL SIMULATION MODEL

3.4.1 General

The 2D numerical model was set up using 4 node plate elements with a regular mesh size of 5 mm. The time step size was set to be regular as well, $1/10^{th}$ of a day. This mesh and time step size was determined through a convergence study, which resulted in an uncertainty of less than 0.1 M% compared to automatic time stepping and 1.25 mm mesh size [5]. The inaccuracies occur right after loading, close to the surface of the beam.

The modelled beam was loaded as a parallel shaped body, like seen in Figure 2. In that way, the material was loaded in its main principal material axis.

The glue lines were not modelled due to earlier mentioned uncertainties concerning this value. These actually should not influence the moisture transport on the longitudinally and tangentially loaded beam, but should on the radially loaded beam.

3.4.2 Results of numerical simulations for 90 mm wide beam

Simulations were performed to validate the numerical program using experiments [11] and diffusion parameters (D = 3e-10 [m^2/s]) obtained from literature [12]. Results of the numerical model are represented by the continuous line and those of the analytical equations by the dashed line, see Figure 8. The experimental results are visualized through markers.

The numerical simulation results show a good agreement with the experiments, so do the analytical solutions. The example shows that the numerical program and the analytical equations can be used to solve simple problems concerning transient moisture content changes.

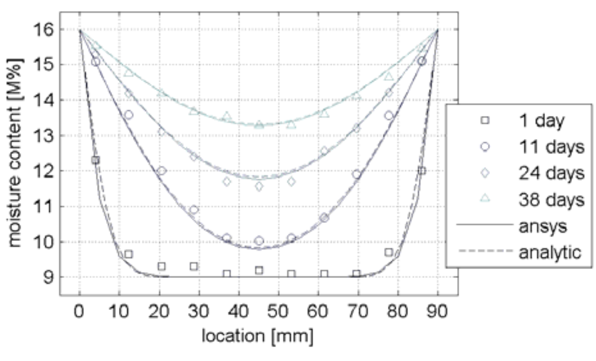

Figure 8: *Comparison of experiments with numerical simulations and analytical equations on 90 mm wide specimens*

3.4.3 Results of numerical simulations for 200 mm wide beam

Simulations of the experimental work at the own laboratories were also performed. As the cross section was 200 mm instead of 90 mm, these had to be performed over a longer period of time. The simulations were performed up to a period of 360 days, although the tests were carried out for roughly 500 days. The results are illustrated in Figure 9. The simulations and the analytical equations are plot through the continuous and dashed line, respectively. Input parameters used in the simulations are mentioned in Table 1. The simulations were performed for a moisture content increase from 12 M% to 20 M%. It should be noted however that the expected moisture content was 24 M%, as formulated by Simpson.

Overall, the simulations show a good agreement with the experimental values until a period of 180 days. At 360 days, higher differences between simulations and experiments are observed. The numerical and analytic simulations show very close overlap. Although most diffusion parameters show a dependency on moisture content, negative for longitudinal loading and positive for transverse moisture diffusion, the constant values given in Table 1 give a reasonable estimation of the moisture content developments.

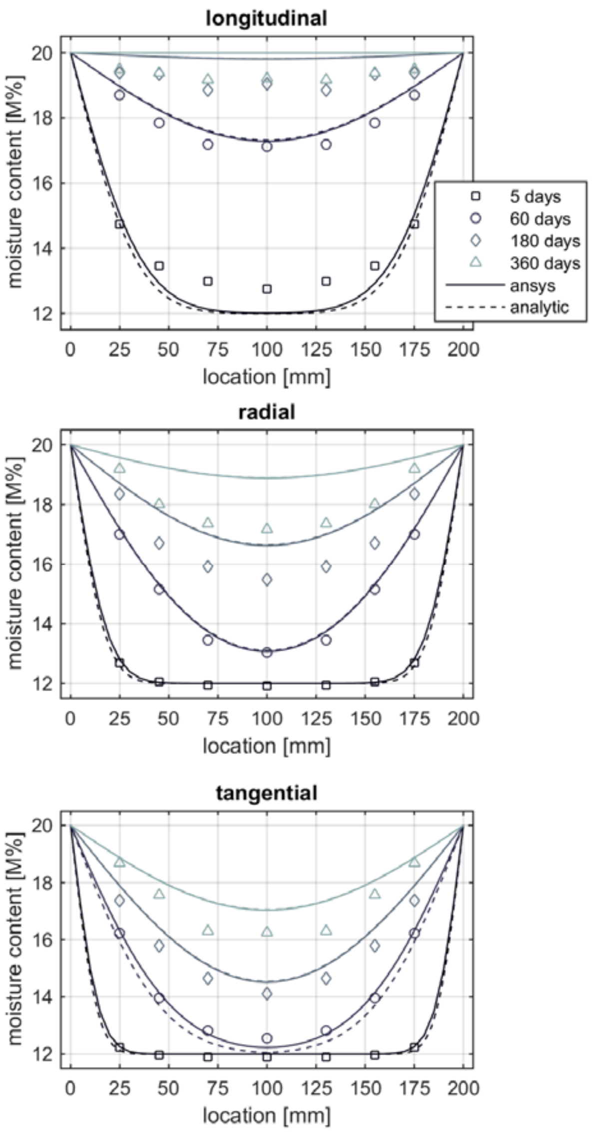

Figure 9: Comparison of laboratory experiments with simulations and analytical equations on 200 mm wide specimens

The differences between 180 days and 360 days of loading of the longitudinally loaded block shows minimal differences, indicating that an equilibrium moisture content has been achieved. At day 5, differences between experimental values and simulations are observed as well. The dependency of diffusion constants is expected to be the cause of the differences found after this short loading period, see Figure 7.

Although it is expected that the moisture diffusion should actually speed up as higher moisture contents are achieved in the radial and tangential moisture diffusion, it appears to slow down instead. This could be due to measurement uncertainties or discrepancy between theory and practice. Most of the moisture diffusion values found in literature are measured through the static cup method [7], [8], determined through small increases in moisture content. Other literature suggests that large non-Fickian effects can be found as the moisture content approaches the equilibrium moisture content in large transient loads [10]. This effect was primarily investigated for moisture diffusion in small samples of approximately 10 to 20mm.

3.5 RESULTS OF NUMERICAL SIMULATIONS FOR 800 MM WIDE BEAM

Experiments on the 800 mm wide specimens were also simulated. These diffusion parameters were not derived separately, so were equal to the ones used for the 200 mm wide beams.

The comparison between the experimental values and the simulations are observed in Figure 10. The experimental values for the radial moisture content development could not be obtained for all the shown moments. The tests ended close to loading day 310.

As the figure shows, moisture content hardly progresses in the centre of the specimens, even after the extensive loading period. Apart from that, the differences between the experimental values and the simulated values suggest that the diffusion values for the larger blocks might be too low. Literature suggests that diffusion values depend on many factors, also on specimen size [7], but don’t say how.

3.6 RESULT OF NUMERICAL SIMULATIONS FOR REALISTIC SEASONAL CLIMATE VARIATIONS ON A BRIDGE

Finally, two simulations were performed for more realistic ambient climate changes. First simulations were performed for the climate measured during monitoring campaigns at the Altdorf weather station, a location close to a bridge used in earlier monitoring campaigns [17]. The second was done for an ice rink. In these calculations, only the numerical model was used.

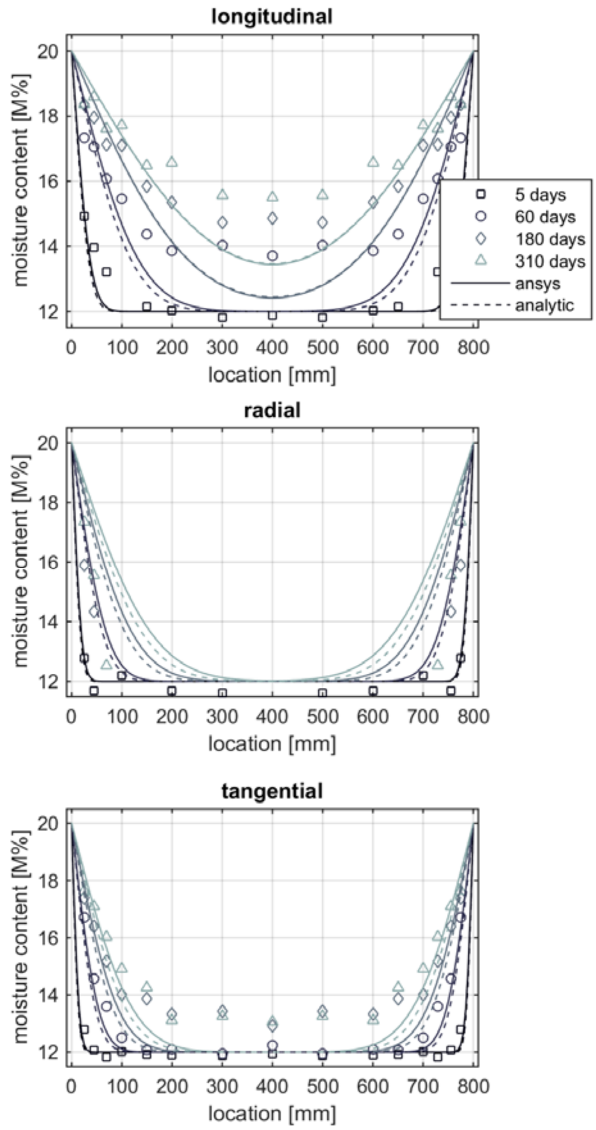

Figure 10: *Comparison of laboratory experiments with simulations and analytical equations on 800 mm wide specimens.*

Fick's model was applied, in combination with Simpson's equations to calculate the sorption isotherms, to calculate the moisture content distribution over a 200 mm wide cross section. This is a simplified approach, because as literature mentions, Fick's model is appropriate for wetting, not for drying or for cyclic loading. Apart from that, the moisture content at the surface of the beam depends on factors like wind or possible contact with direct sunlight. These factors reduce the equilibrium moisture content at the beam surface, which in turn also affects the moisture content distribution under the surface. The daily averages of measured relative humidity and temperature were obtained from Swiss meteorological monitoring stations. The diffusion parameter used was the experimental one for tangential diffusion, listed in Table 1. The model was loaded as a parallel shaped body again.

First the moisture content development over the year 2014 was calculated, illustrated in Figure 11. The moisture content development was calculated at different

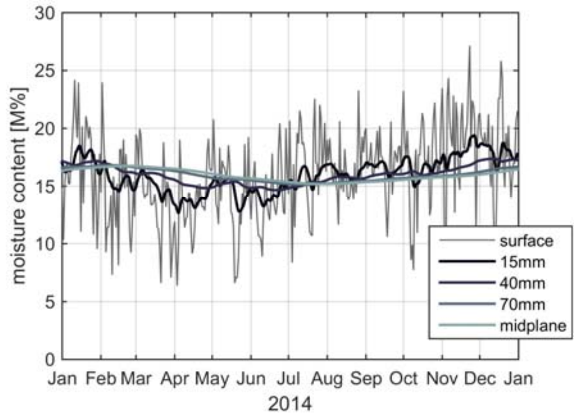

Figure 11: *Moisture content time traces at different depths of the beams surface throughout 2014*

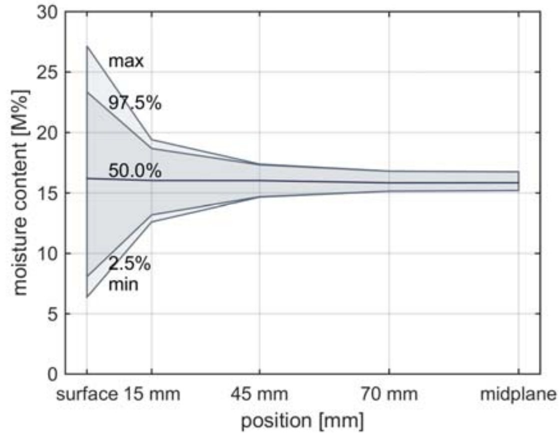

Figure 12: *Minimum, maximum and percentiles of moisture content calculated for a 200 mm wide beam*

depths from the surface: 15 mm, 45 mm, 70 mm, and midplane. The thin line at the surface represents the applied load.

As observed, the moisture content at 70 mm depth and at the midplane varies between 15 M% and 17 M%. The moisture content right below the surface, at 15 mm depth, does not exceed 20 M%, meaning that actually only the surface is affected by the highly varying moisture contents.

Similar calculations were made over a 10 year period. The minimum, 2.5%, 50%, 97.5%, and maximum moisture contents over this period is plot in Figure 12. Over the 10 years for which the moisture content was calculated, variations at the midplane stay under 2 M%. These are similar at 70 mm depth from the surface. Closer to the surface, at 15 mm depth, the moisture content barely reaches the 20 M% needed for a higher building class.

3.7 RESULT OF NUMERICAL SIMULATIONS FOR REALISTIC SEASONAL CLIMATE VARIATIONS IN AN ICE RINK

A similar case was set up or ice rink B2 mentioned in [18]. The observed maximum moisture content during the period in which ice covered the rink, was estimated to be about 19 M%. During summer the minimum was about 7 M%. The load used in the simulation is simplified from the actual measured load, which shows smoother transitions, see Figure 13.

The highest moisture content variations are seen close to the surface, where the moisture content almost reaches 19 M% at the end of the wetting period, and 7 M% at the end of the drying period. The moisture content at the 70 mm and deeper only varies between 10 and 16 M%.

4 DISCUSSION

Proper models to calculate moisture content developments in the future need to include more parameters, a couple of suggestions are:

- Moisture content dependent diffusion values,
- Application of non-Fickian moisture diffusion models,
- Using ad- and desorption curves to calculate the equilibrium moisture content at the surface of the beam,
- Including effects like wind, exposure to direct sunlight, and
- If applied, influence of coating.

The use of Fick's model however is expected to give a good approximation already. Instead of including all above mentioned effects, another approach could be to work with expected uncertainties to calculate conservative values.

The analyses of the experimental results show, that the moisture content distribution over the cross section can be divided in an active and passive zone, as shown in Figure 14 and Figure 15. The distribution of the moisture content along the radial or tangential direction is not converged even after one year of the intensive adsorption process. Similar results are observed within the numerical simulation where the climate changes daily on a cross section of 200/200/200 mm in tangential direction, as shown in Figure 11, and Figure 12.

Daily or weekly climate changes result in a change of moisture content only in the outer zone of the cross section, which is relatively small for example for the cross sections of large timber bridges. However, only a

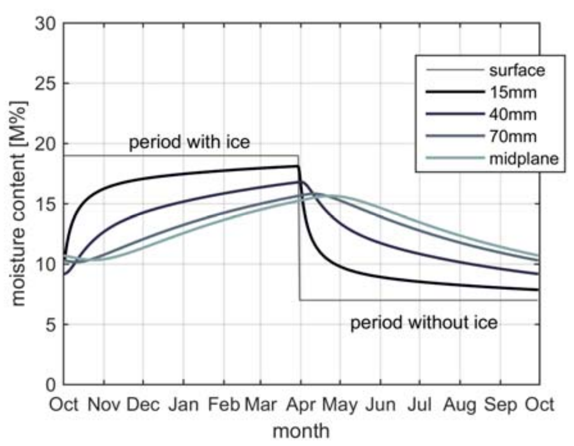

Figure 13: Suggested moisture content development in an ice rink

constant service class is currently used for the design. As proposal, a differentiation of the service class over the cross section could be used for the enhancement of existing load capacities (active zone = SC 3, passive zone = SC 2) and, therefore, increase the capacity of the structure, depending on its location and operational conditions.

5 CONCLUSION AND VIEW

The distribution of the moisture content over the time and the cross section could be experimentally determined during an adsorption process. For two different sizes and three material directions the distribution over the cross section was determined.

It was shown that the estimation of the moisture content over the cross section can be performed using analytical equations and numerical programs. Furthermore the numerical simulation could successfully applied to a case study of a bridge and an ice rink. The experimental and numerical results reached to support the scientific as well as the practical engineers.

Most of the research on diffusion factors was performed with load types and specimen sizes that are only little encountered in reality. Further efforts should focus on better determination of important factors affecting the moisture content in large structures and methods to determine these.

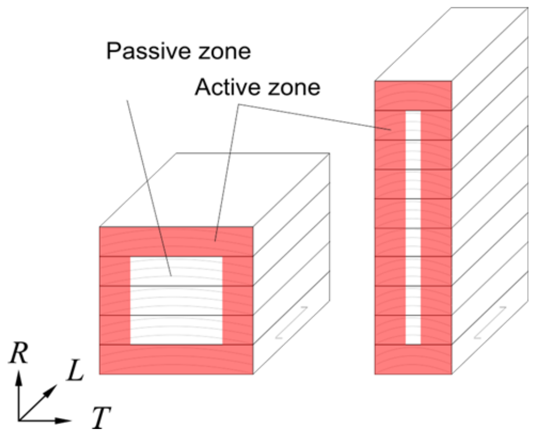

***Figure 14:** Differentiation of cross section in active and passive zone*

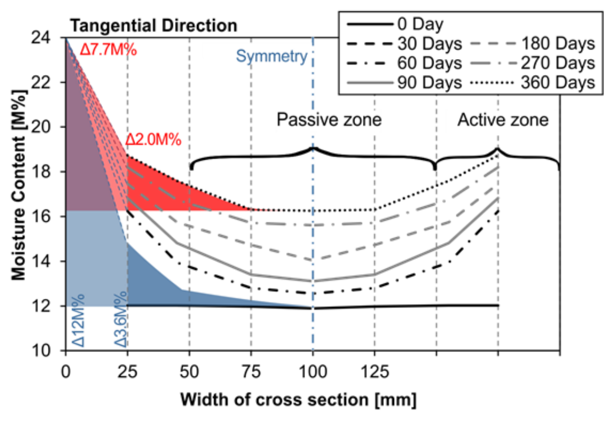

***Figure 15:** Experimental results of moisture distribution in tangential direction for the adsorption process, 200/200/200 mm*

Finally, introduction of an active and passive zone in structures could enhance the load bearing capacity of structures. As shown through simulations, maximum moisture contents for the inner part of the cross section (passive zone) are below 20M% and, therefore, belongs to service class 2 where higher modification factors could be applied.

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